

# THE CMS EXPERIMENT

Fermilab at 50  
Anniversary Celebration



Salvatore Rappoccio

 **University at Buffalo** The State University of New York



## First: a personal Thank You for the invitation!

- Me:
  - Professor at the University at Buffalo on CMS
  - Former CDF Member
  - Present involvement at FNAL LPC
  - ~22 years of Fermilab involvement myself!



This means a lot to me personally, so thank you for being a big part of my professional life!

My first graduate student:  
Dr. Maral Alyari, at SiDet, now FNAL postdoc



Disclaimer: I cannot possibly hope to cover everything from LHC and CMS in 25 mins, so bear with me.

## → CMS, LHC, and FNAL

- Why are we still here?

### Past

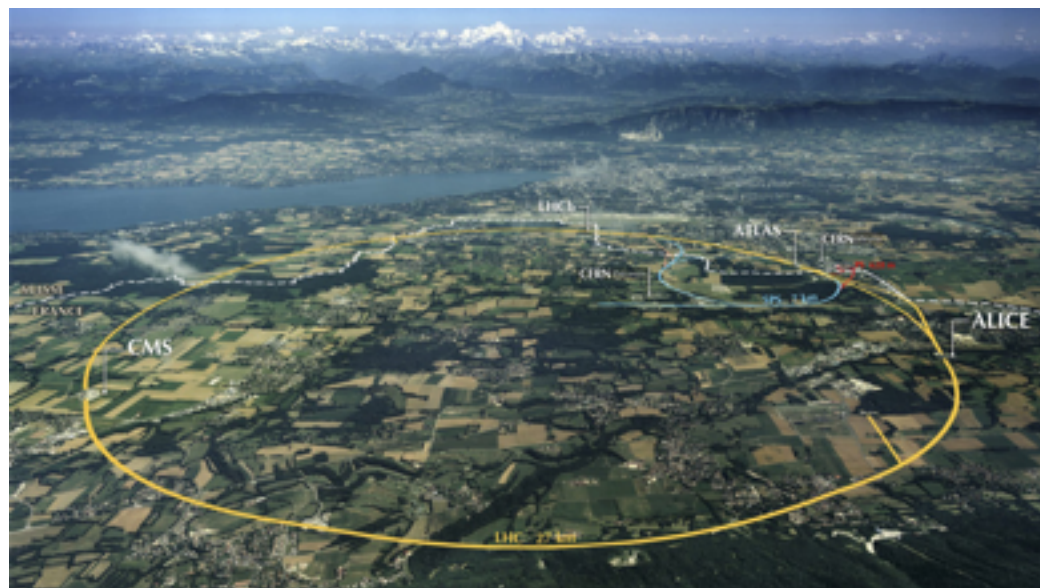
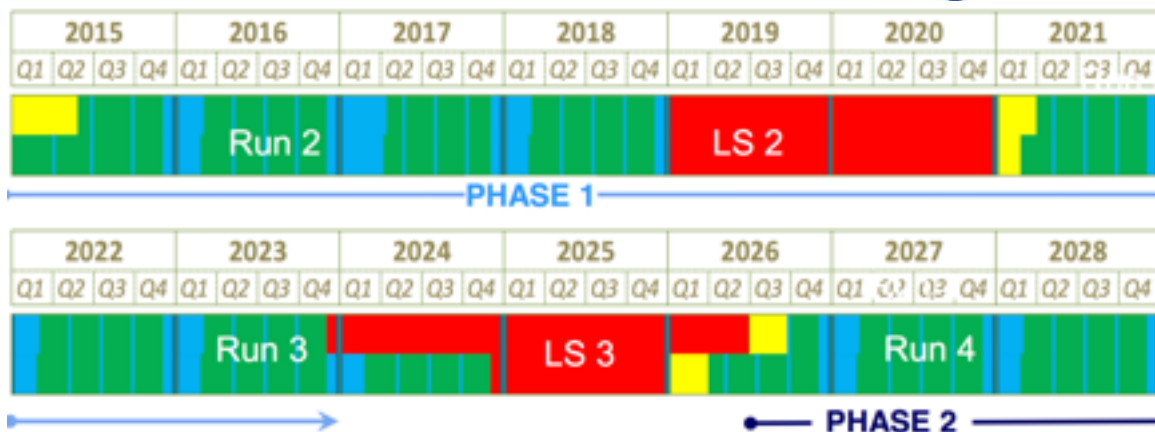
- 2007-2012 (“Run 1”)

### Present

- 2015-2018 (“Run 2”)

### Future

- >2018 (“Run 3” and High-Lumi LHC)







## U.S. Particle Physics: Building for Discovery

*U.S. Particle Physics Strategy*

*Education and Outreach Site*



**Use the Higgs boson as a tool for discovery**

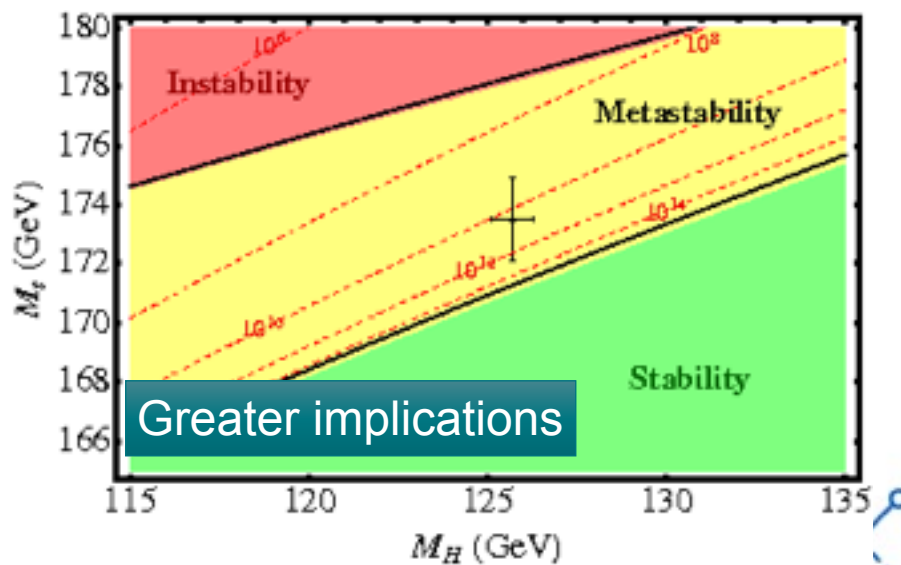
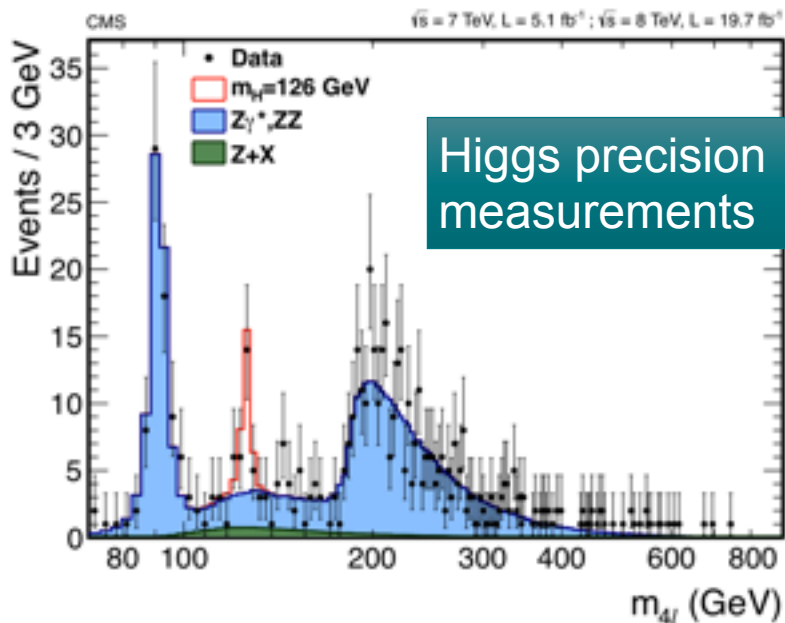
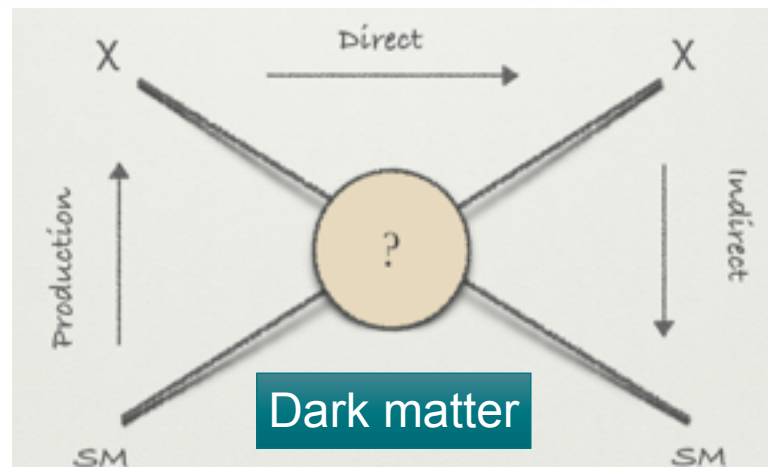
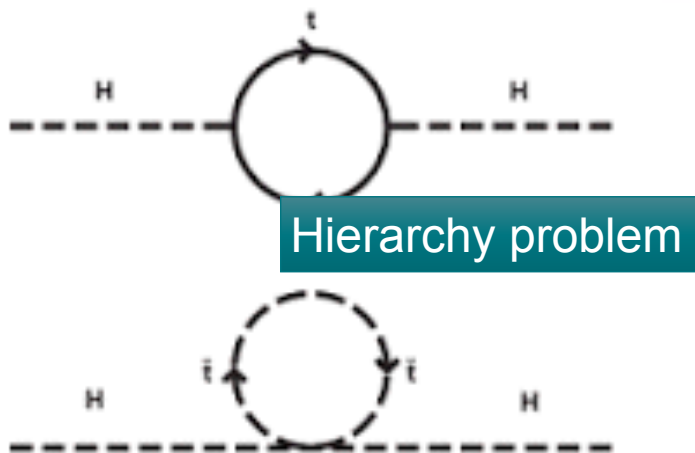
**Identify the new physics of dark matter**

**Explore the unknown**



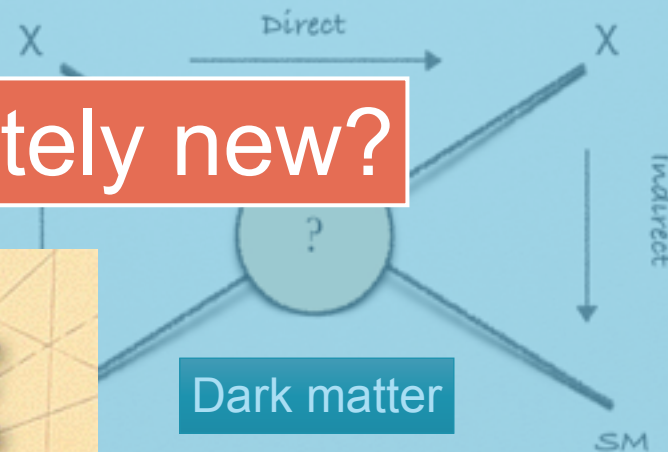


# Why (still) the LHC?



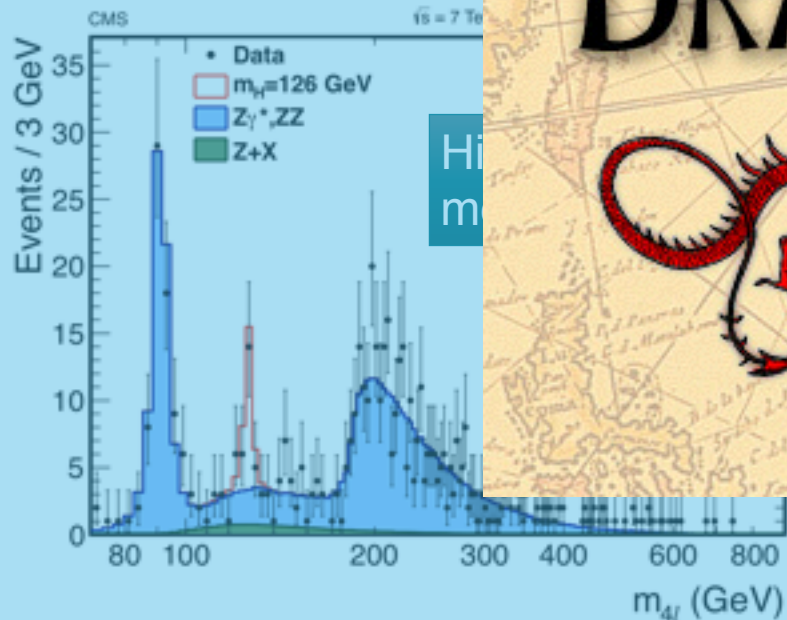
OR something completely new?

Hierarchy problem

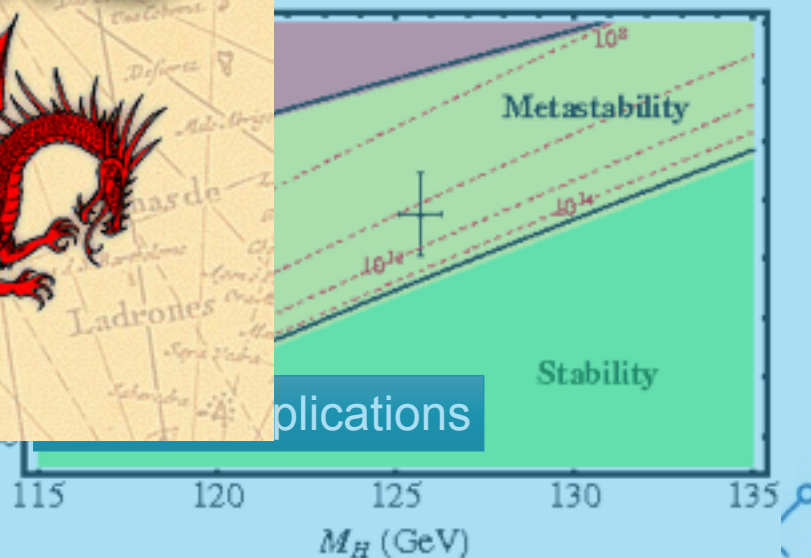


Dark matter

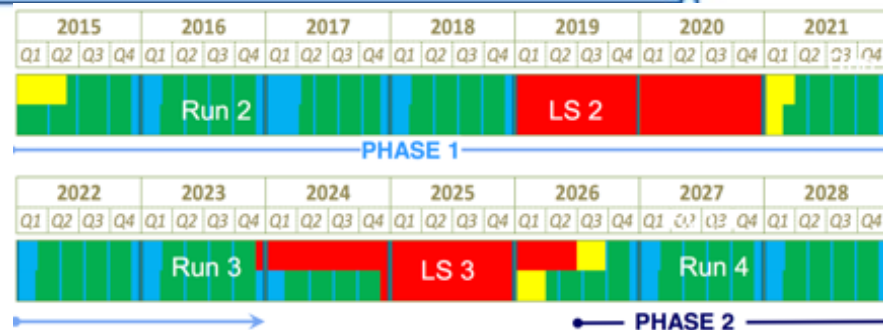
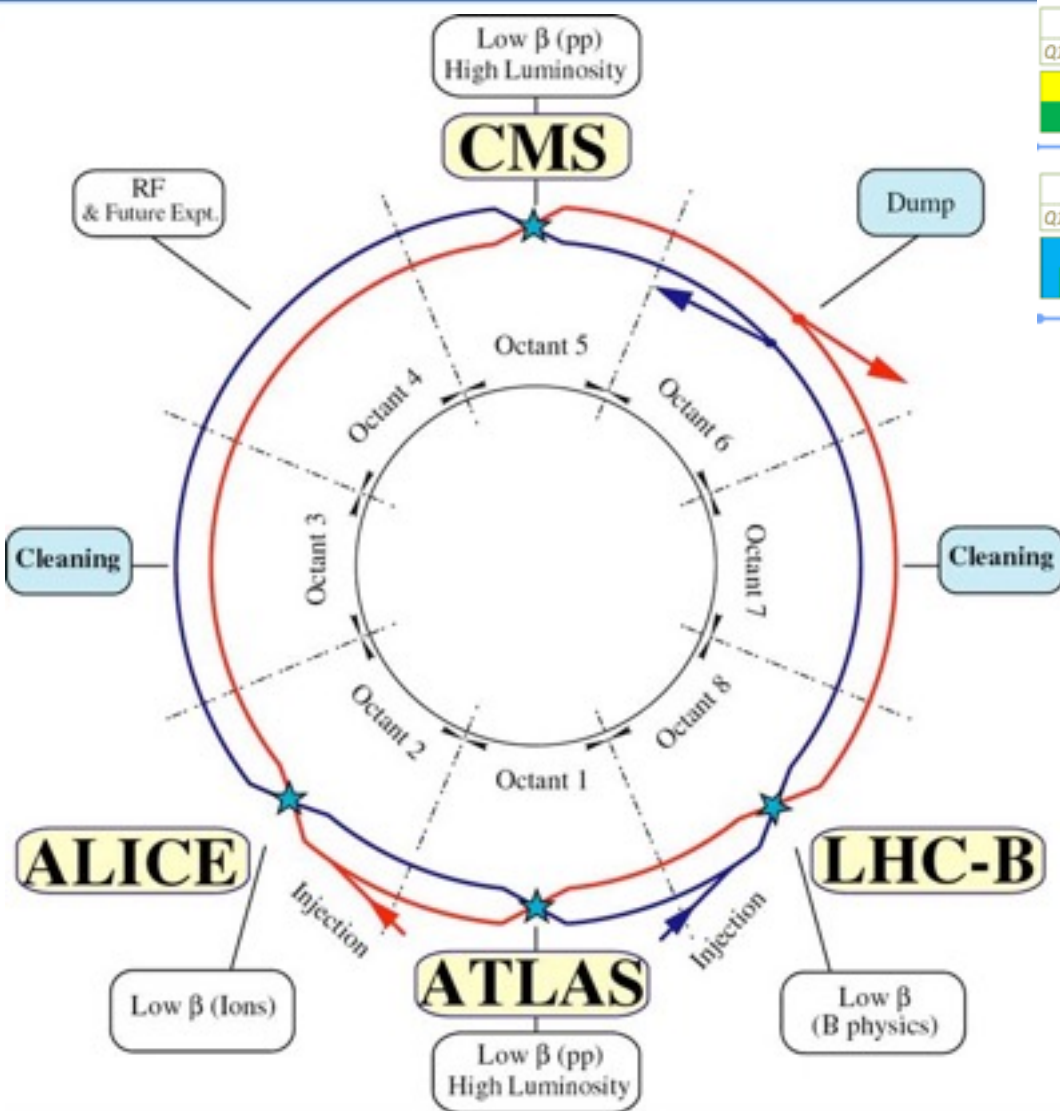
## HERE BE DRAGONS



Hi  
m



Implications



- pp collider in Geneva, Switzerland and surrounding areas in France
- 27 km circumference
- 50-175 m underground
- Restarted May 23rd
- $E_{\text{com}} = 13 \text{ TeV}$
- Expect  $L > 1.7 \text{e}34 / \text{cm}^2\text{-s}$
- Plan on  $\text{O}(50) \text{ fb}^{-1}$  integrated lumi this year



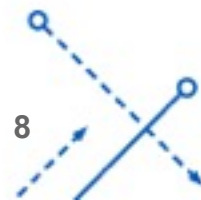
## FNAL built LHC focusing magnets

Also providing extensive technical support throughout the LHC era

## Developing next generation of accelerator magnets for HL-LHC with CERN

LHC Accelerator Research Program (LARP)

Magnet built at FNAL installed in LHC tunnel




**Fermilab**  
 50 Years of Discovery

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## Newsroom

- News and features
- Press releases
- Fact sheets and brochures

## CERN ramps up neutrino program

January 6, 2017 | [Sarah Charley](#)

In the midst of the verdant French countryside is a workshop the size of an all-extension, technicians cut through thick slices of steel with electric saws and



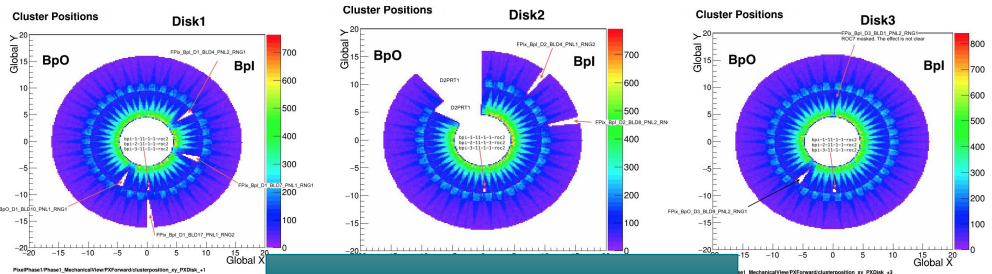
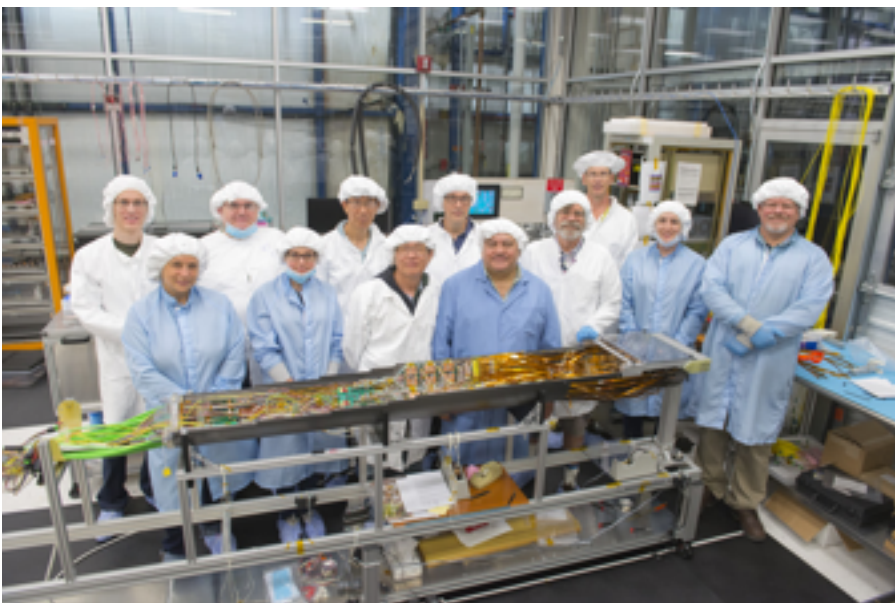
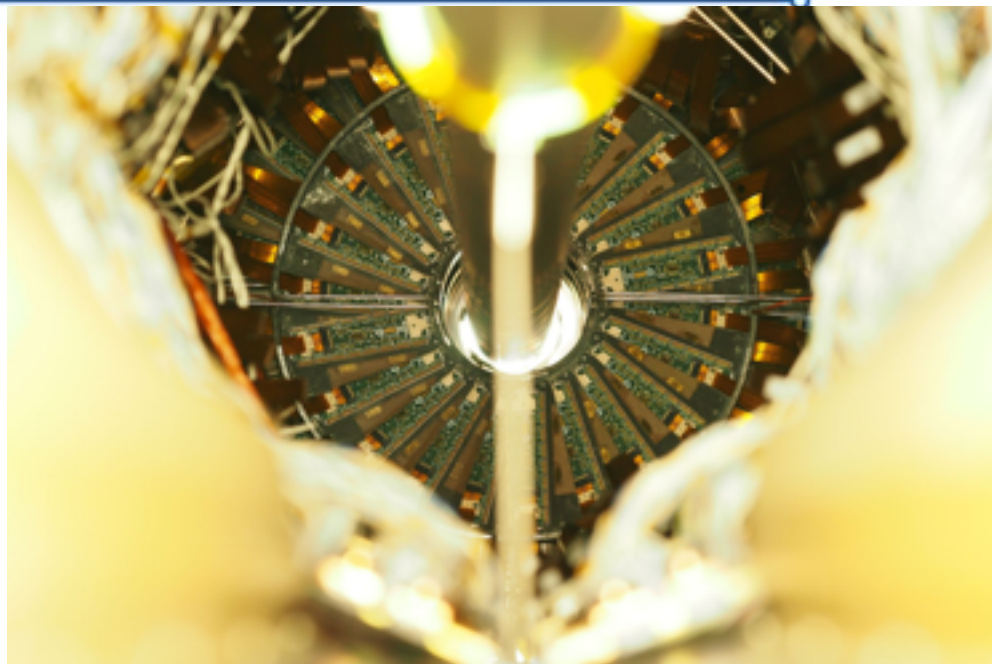
## US/CERN agreement signed collider agreement 2015, neutrino commitment 2017



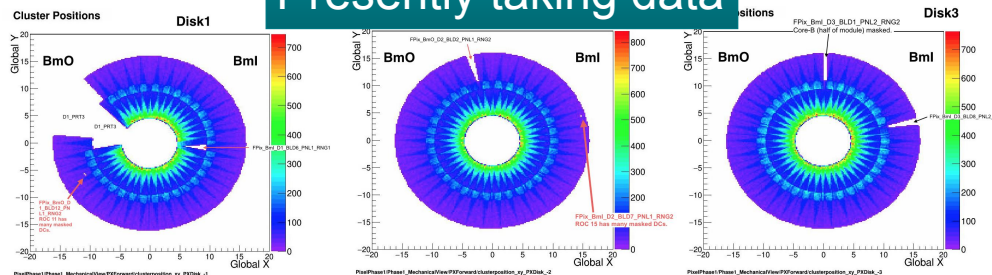
Energy Secretary Ernest Moniz, CERN Director-General Rolf Heuer and NSF Director France A. Córdoba sign a US-CERN agreement at the White House (Image: Ken Shipp/DOE Photo)



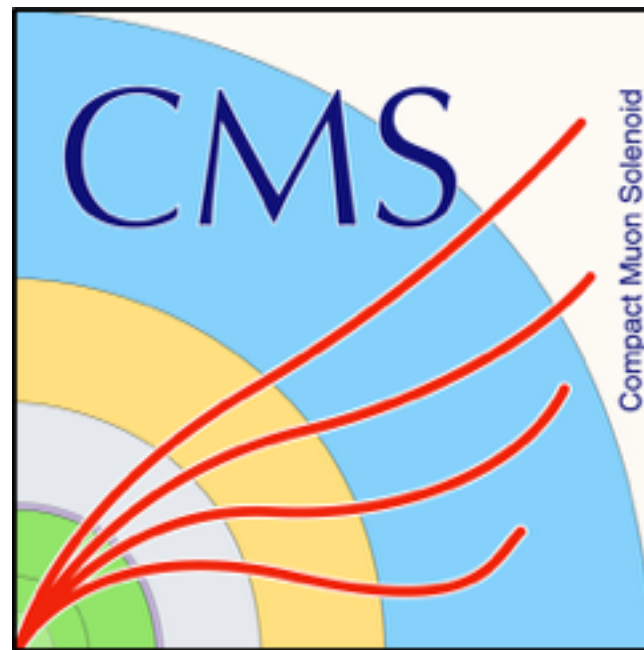
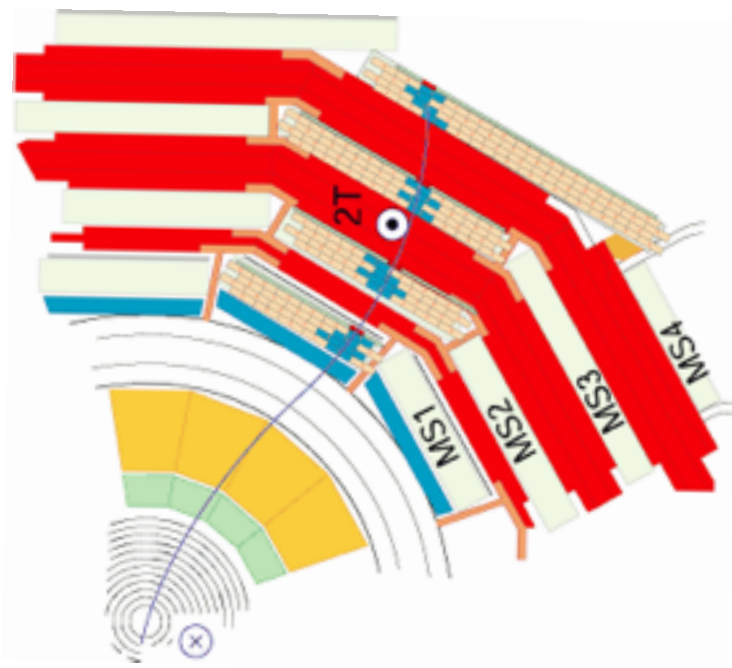
**FNAL contributed significantly to CMS upgrades: forward pixel upgrade built here at SiDet!**



**Presently taking data**







## CMS: Experiment E-892 at FNAL

- Extended presence of FNAL at CMS for years
- Current spokesperson: Joel Butler of FNAL

## “Tier 1” Computing Facility

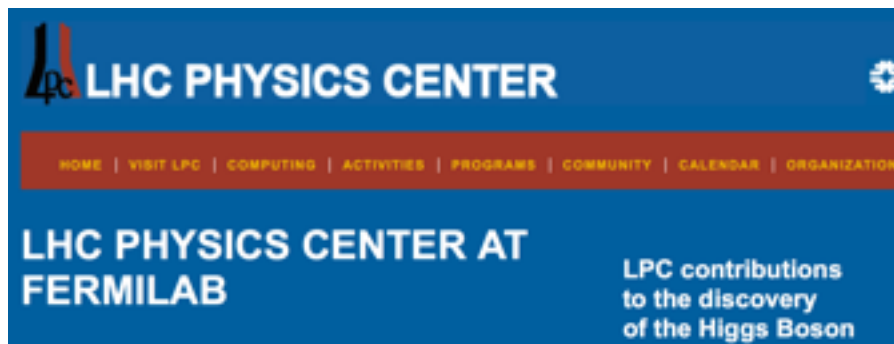
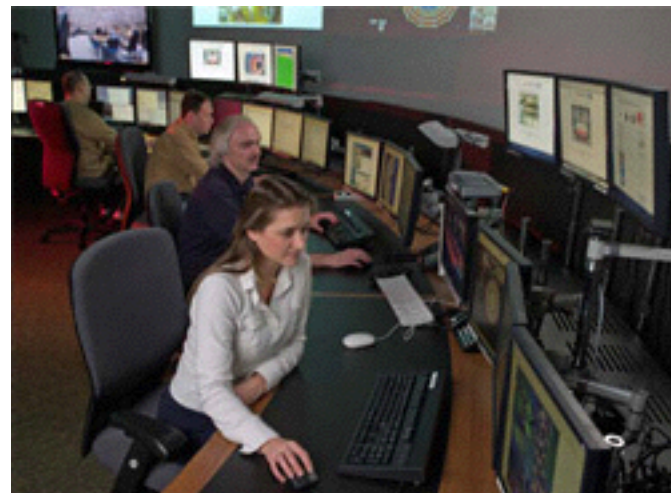
- Handles ~half of T1 computing

## Remote Operations Center

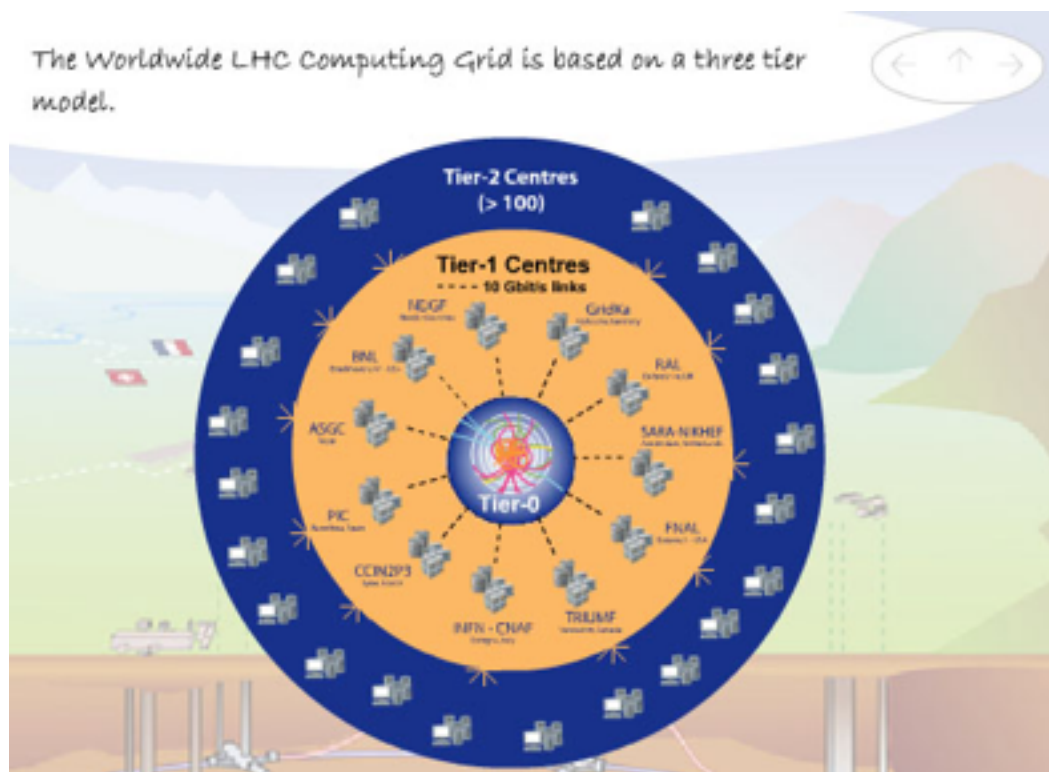
- Communication directly with CMS at Point 5 (even can take remote shifts!)

## LHC Physics Center (LPC)

- Successful establishment of “brick and mortar” facility for physics (70% of US CMS institutions!)
- Involved in hundreds of papers and other work



See next talk by Jim Amundson!





## CMS, LHC, and FNAL

- Why are we still here?

### → Past

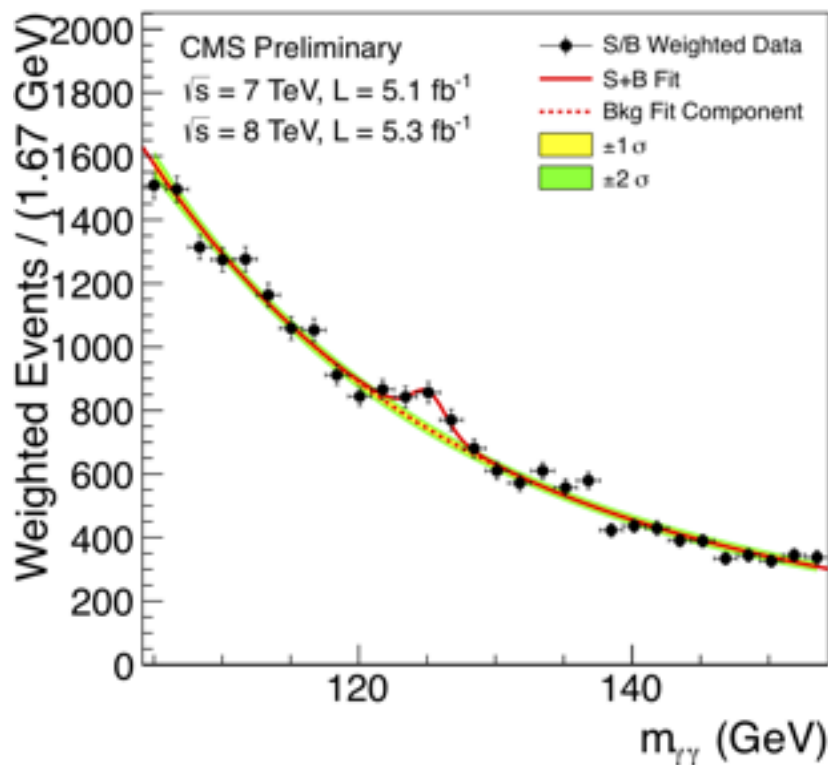
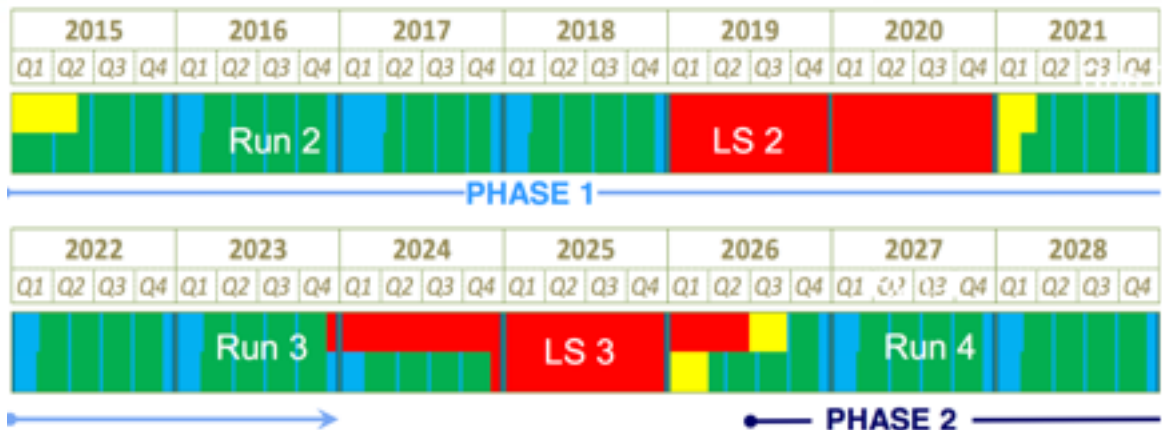
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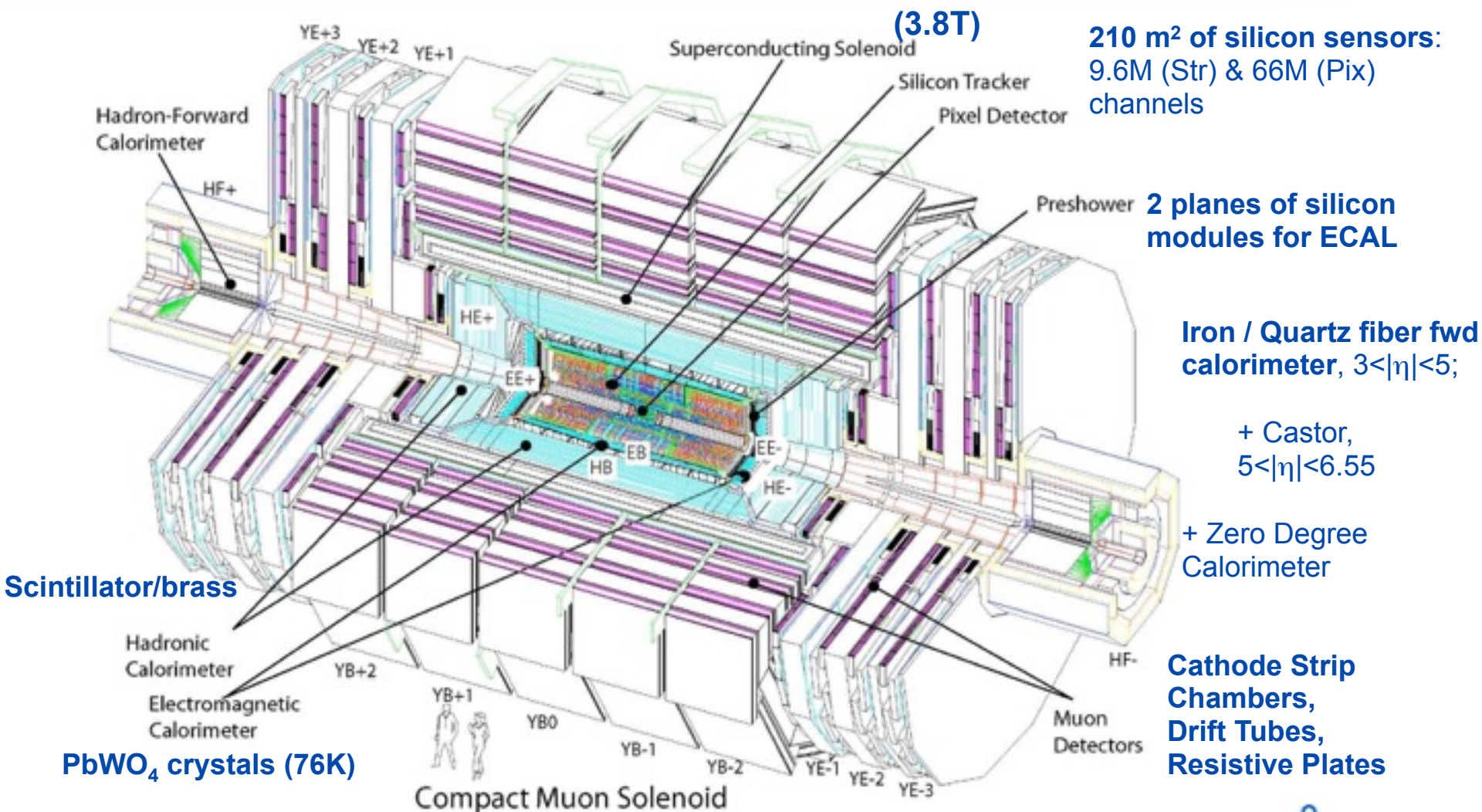
### Present

- 2015-2018 (“Run 2”)

### Future

- >2018 (“Run 3” and High-Lumi LHC)

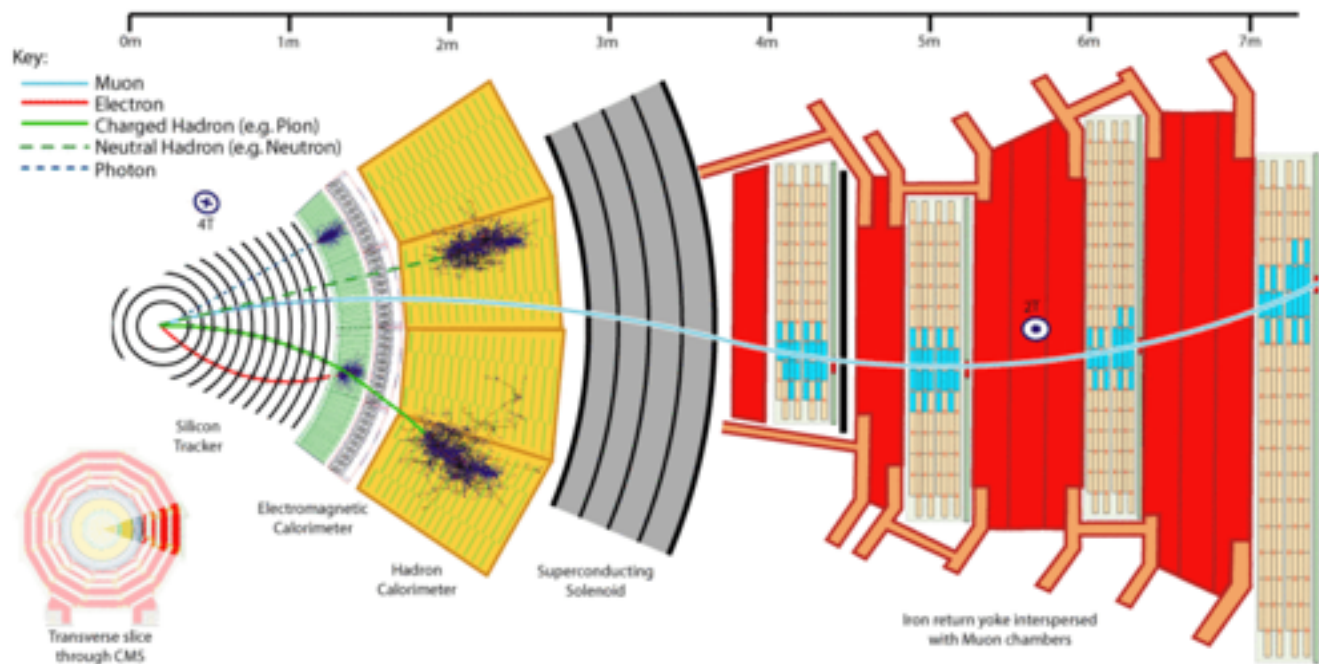




Strong B field, small radius of curvature?

## Particle flow!

- Separate and identify each stable particle
- Combines information from all subdetectors





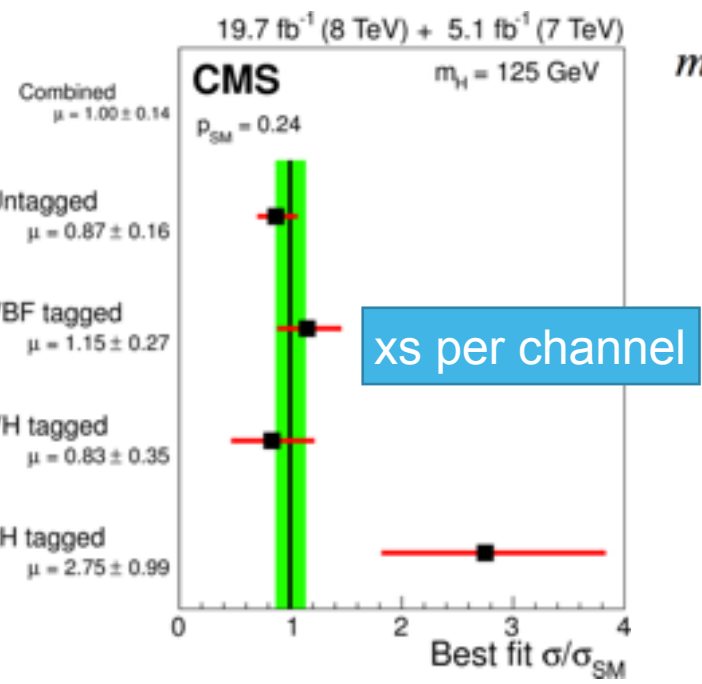
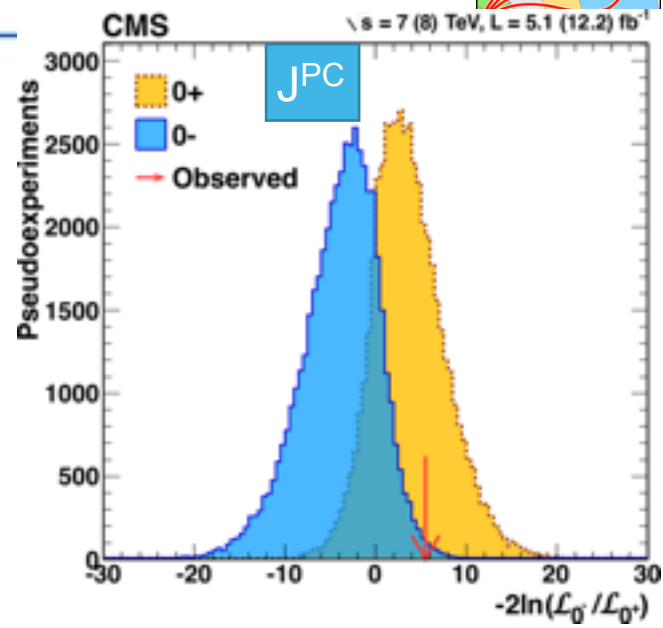
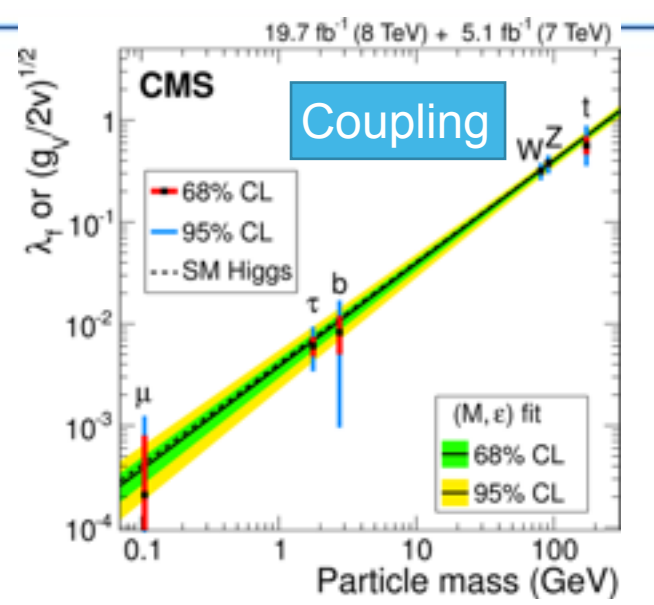


# The Past: Run 1 Physics Results

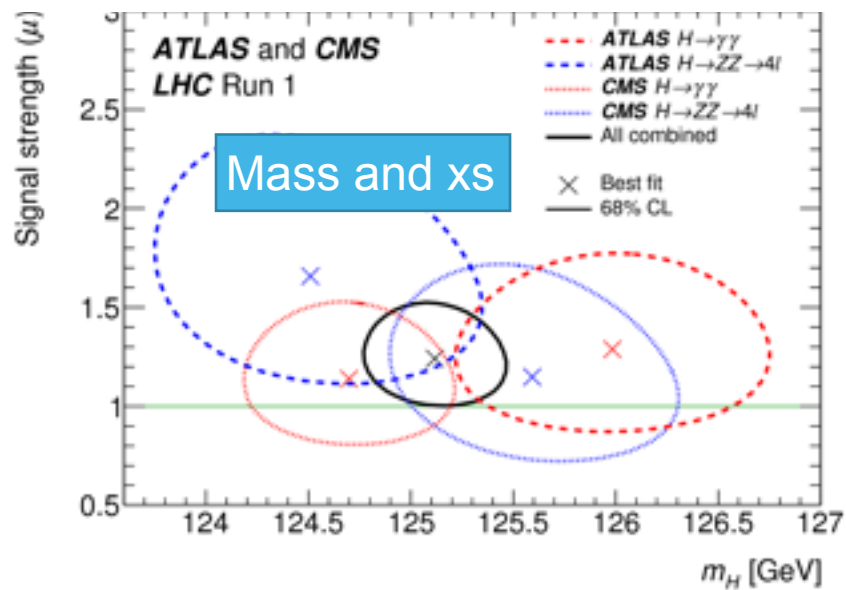


## Higgs Physics:

- Discovery
- Couplings
- Spin properties
- Mass
- Cross sections
- Rare decays

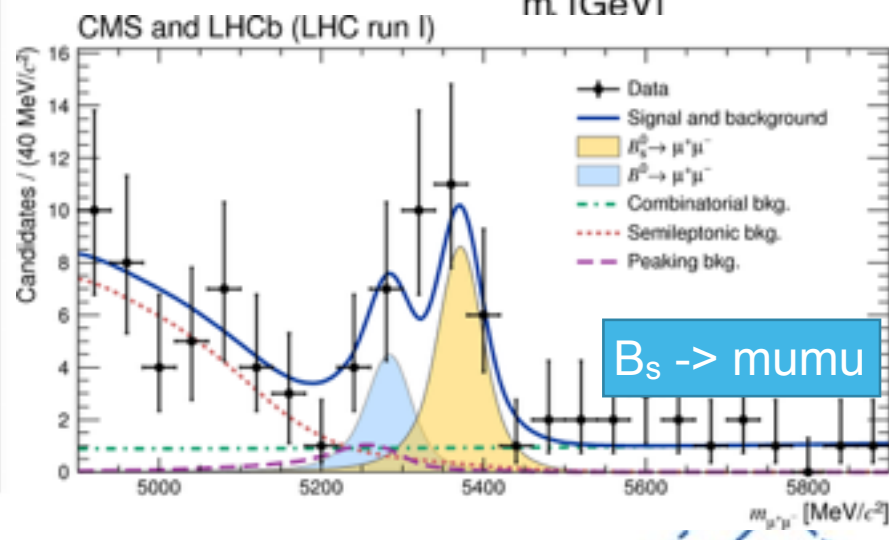
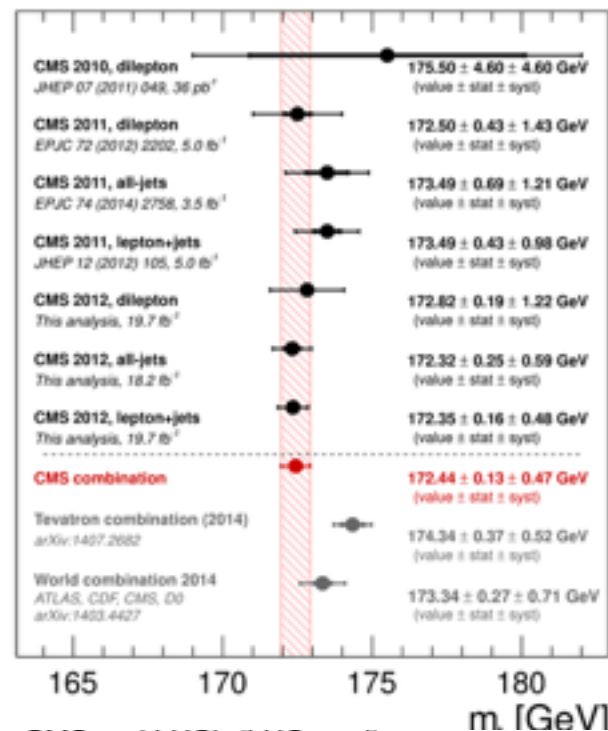
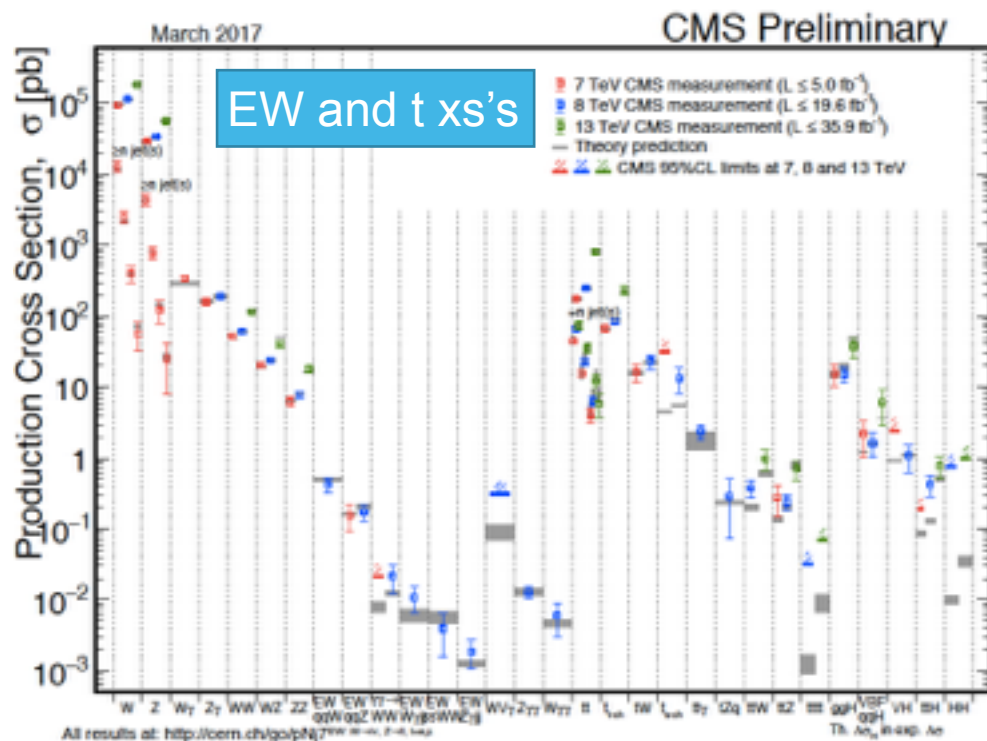


$m_H = 125.09 \pm 0.24$  GeV =  $125.09 \pm 0.21$  (stat)  $\pm 0.11$  (syst) GeV,



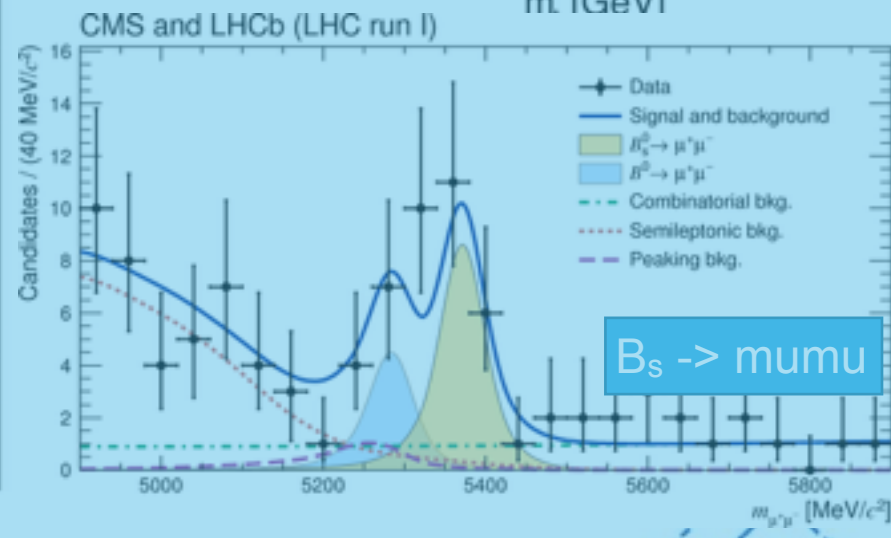
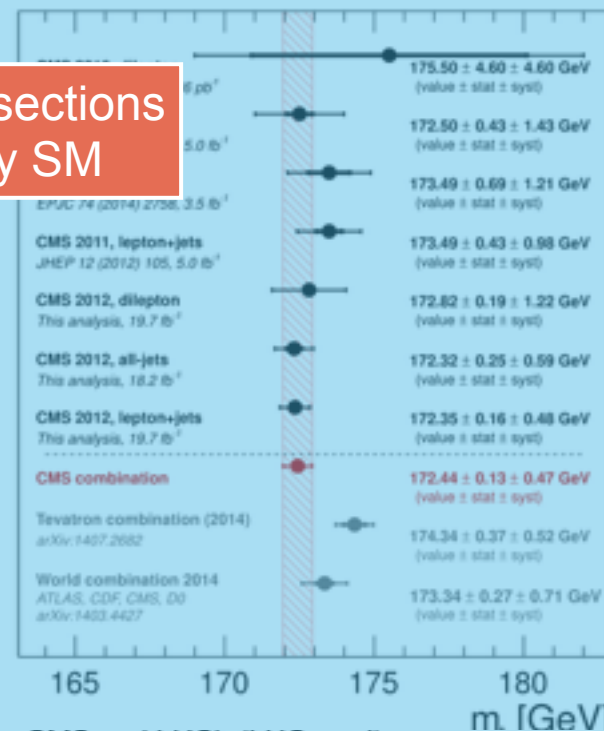
## SM Measurements

- W, Z
- Jets
- Top quark
- Bottom quark
- Forward physics



~10 orders of magnitude of cross sections  
measured at the LHC, predicted by SM

- 
- CMS Preliminary**
- EW and  $t\bar{t}$ 's**
- Production Cross Section,  $\sigma$  [pb]
- 7 TeV CMS measurement ( $L \leq 5.0 \text{ fb}^{-1}$ )
  - 8 TeV CMS measurement ( $L \leq 19.6 \text{ fb}^{-1}$ )
  - 13 TeV CMS measurement ( $L \leq 35.9 \text{ fb}^{-1}$ )
  - Theory prediction
  - CMS 95%CL limits at 7, 8 and 13 TeV
- All results at: [http://cms.cern.ch/cgi-bin/TYPO-00-000\\_2-00\\_Supp](http://cms.cern.ch/cgi-bin/TYPO-00-000_2-00_Supp)

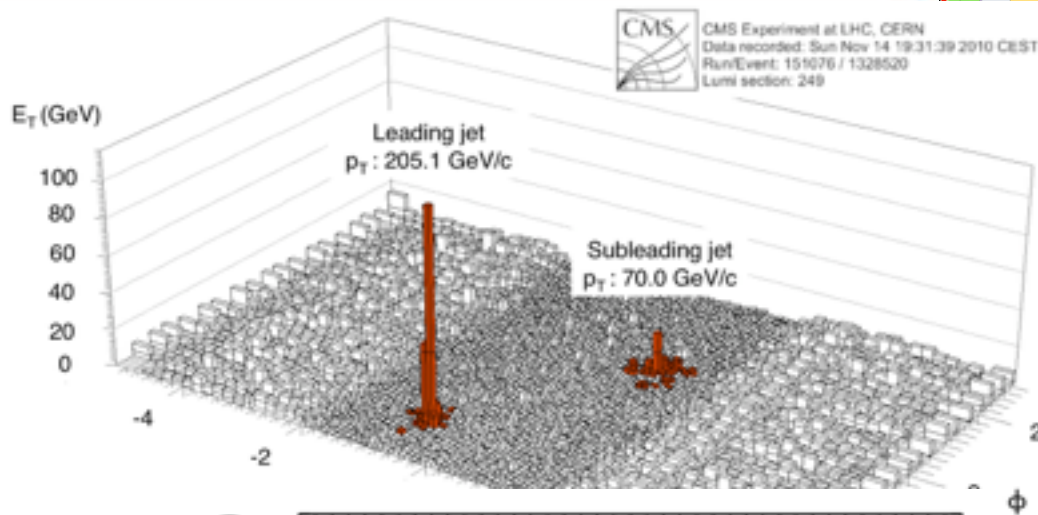






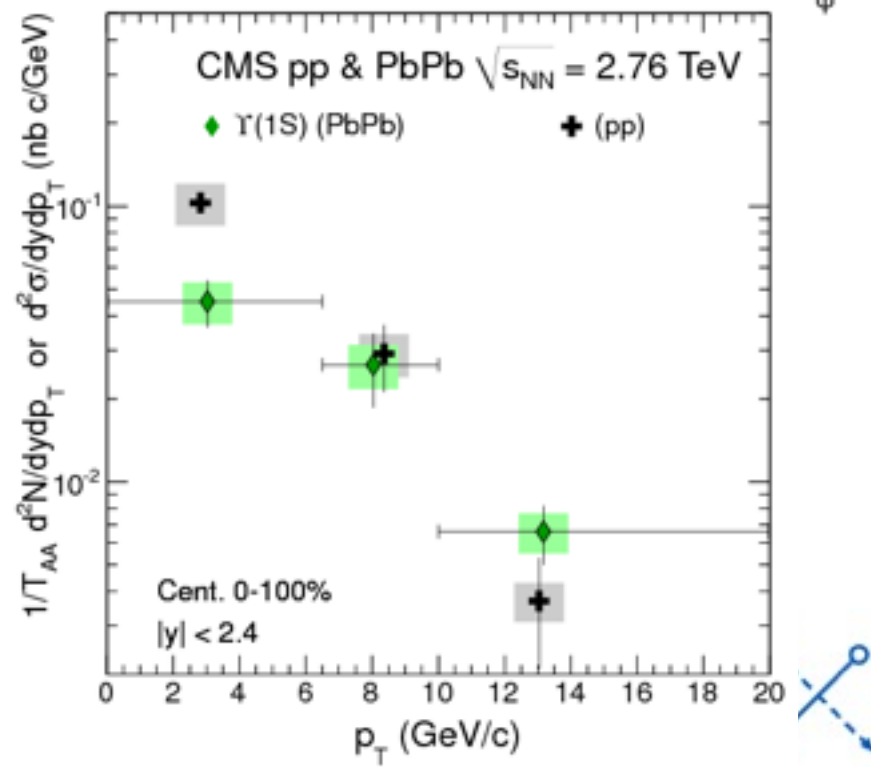
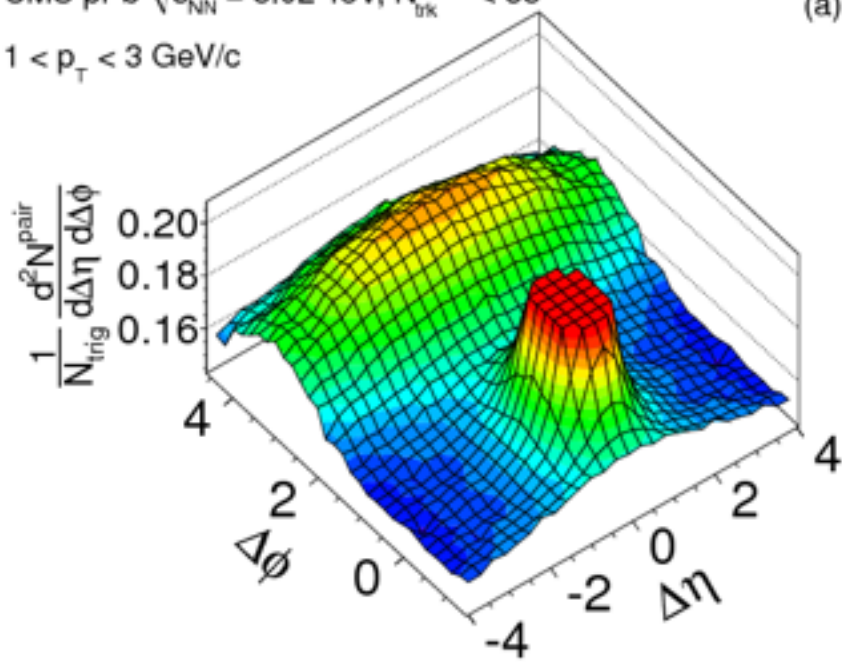
## Heavy Ions

- Jet quenching demonstrated
- Quarkonium (upsilon) suppression
- Particle-particle correlations
- Etc



CMS pPb  $\sqrt{s_{NN}} = 5.02$  TeV,  $N_{trk}^{offline} < 35$

$1 < p_T < 3$  GeV/c



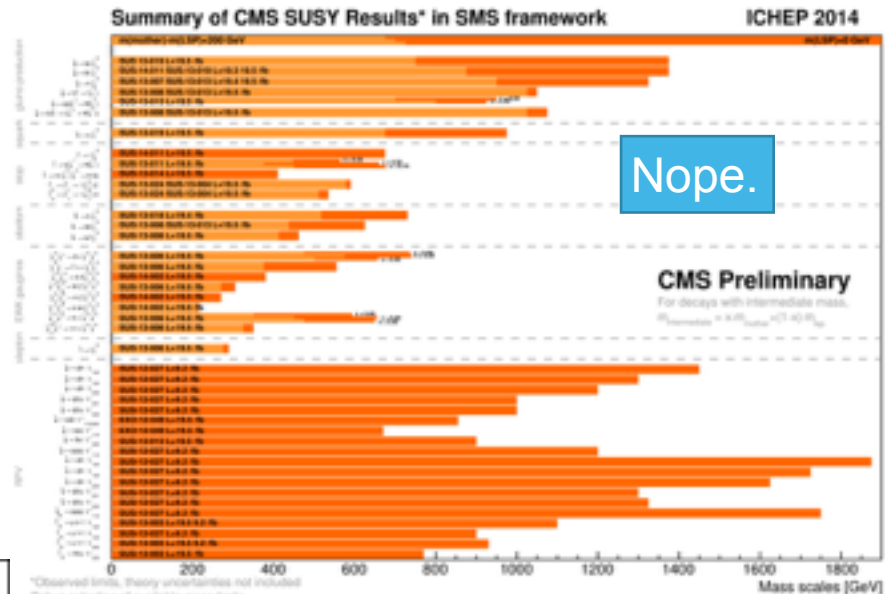
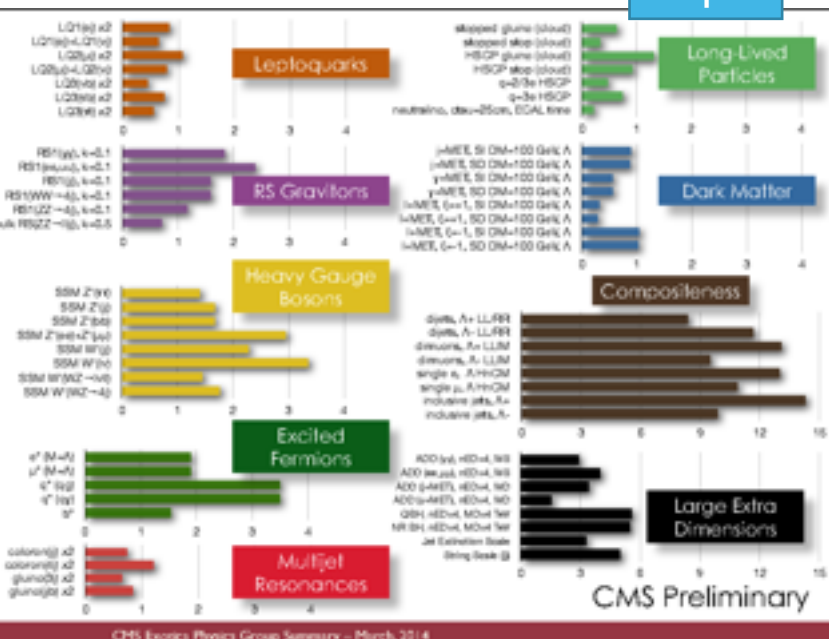


# The Past: Run 1 Physics Results

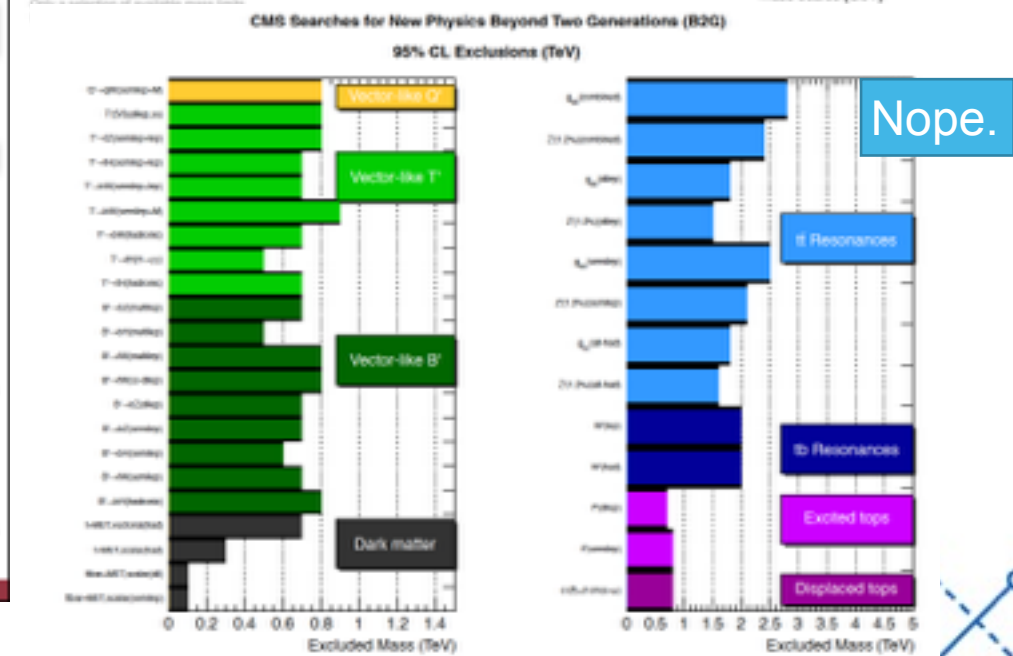
# BSM Searches

- Supersymmetry
- Extra dimensions
- Dark matter
- Long lived particles
- Rare production and decays
- Many others

Nope.



Nope.



Nope.

## CMS, LHC, and FNAL

- Why are we still here?

## Past

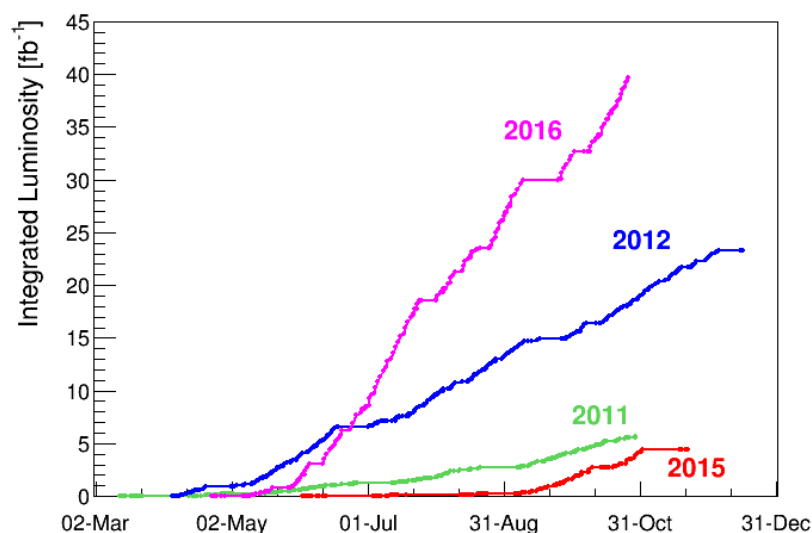
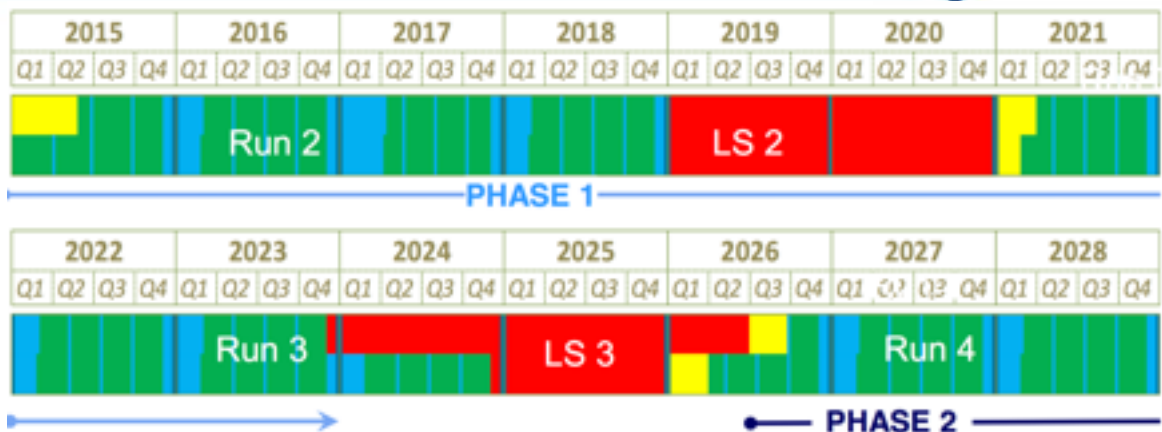
- 2007-2012 (“Run 1”)

## ➔ Present

- 2015-2018 (“Run 2”)

## Future

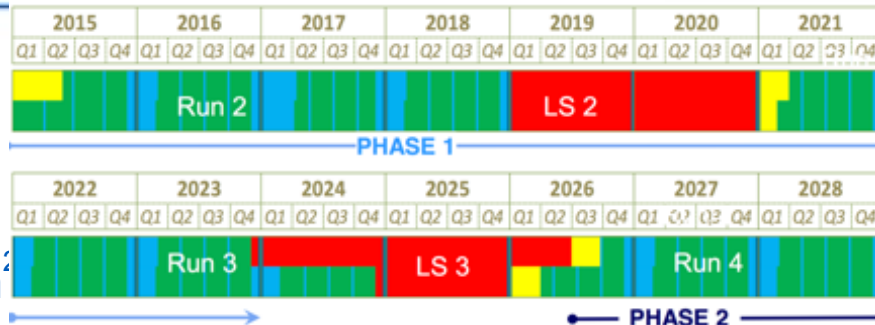
- >2018 (“Run 3” and High-Lumi LHC)





## Long shutdown 1 (<2015)

- Replaced splices for accelerator magnets
- Operating at 13 TeV
- Luminosity increased to  $\sim 1.4 \times 10^{34} / \text{cm}^2 \text{s}$
- 27 Interactions / crossing!

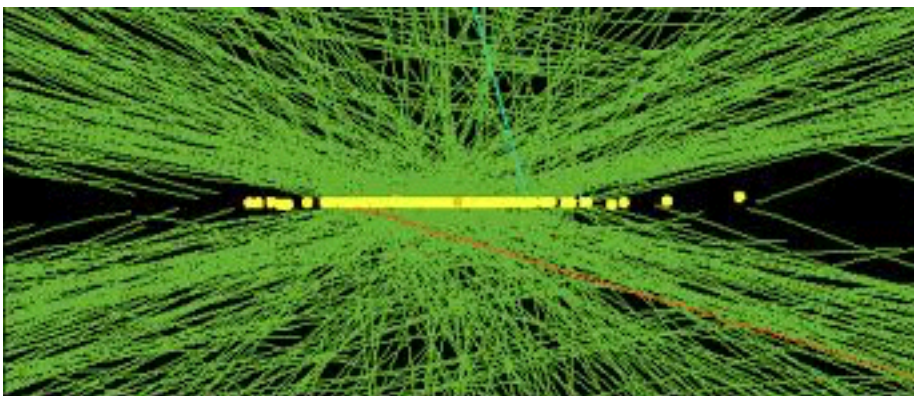


## Extended year-end technical stop (2016-2017)

- Magnet training campaign
- Replacement of LHC dipole in sector 1-2
- Many other activities



Info from Rende Steerenberg  
US CMS Collaboration Meeting 2017 24



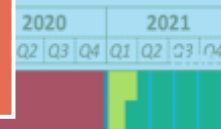


# LHC Status as of yesterday when I uploaded my talk:



## Long shutdown

- Replaced splices for accelerator



LHC Page1

Fill: 5768

E: 450 GeV

07-06-17 21:49:31

## PROTON PHYSICS: INJECTION PHYSICS BEAM

BCT TI2: 0.00e+00

I(B1): 2.11e+14

BCT TI8: 0.00e+00

I(B2): 2.38e+14

TED TI2 position: **BEAM**

TDI P2 gaps/mm

up: 109.78

down: 110.23

TED TI8 position: **BEAM**

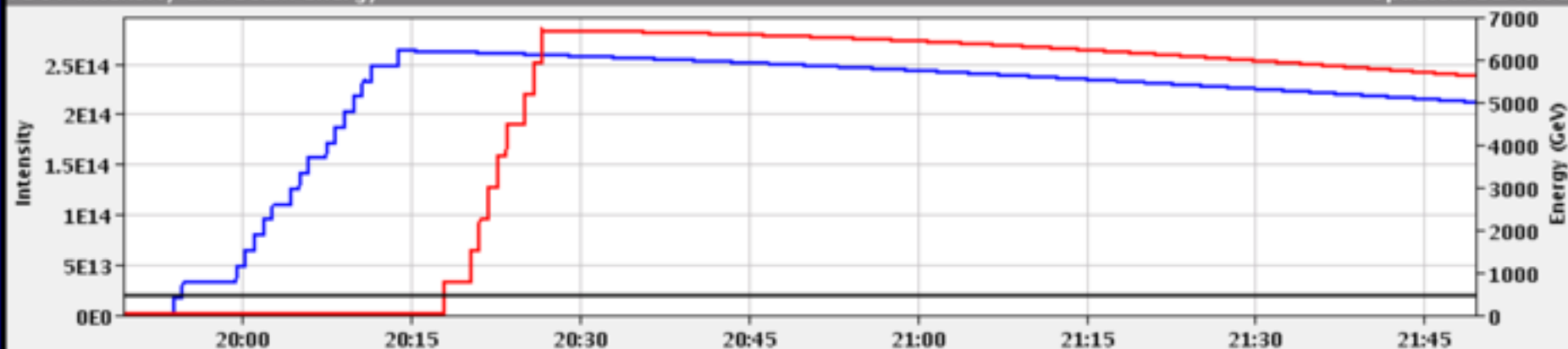
TDI P8 gaps/mm

up: 80.01

down: 79.87

FBCT Intensity and Beam Energy

Updated: 21:49:31



## Pixel tracker:

Barrel and forward completely replaced:  
Now 4-layer barrel, 3-disk endcap (4 hit coverage)  
Reduced material, CO2 cooling  
Electronics upgrade

## Hadronic calorimeter

Endcap: Installation of new RO boxes (delayed till end of 2017), add new SiPMS  
Forward: new PMTs  
Outer: replace HPD with SiPMs  
Depth segmentation added

# Muon Systems

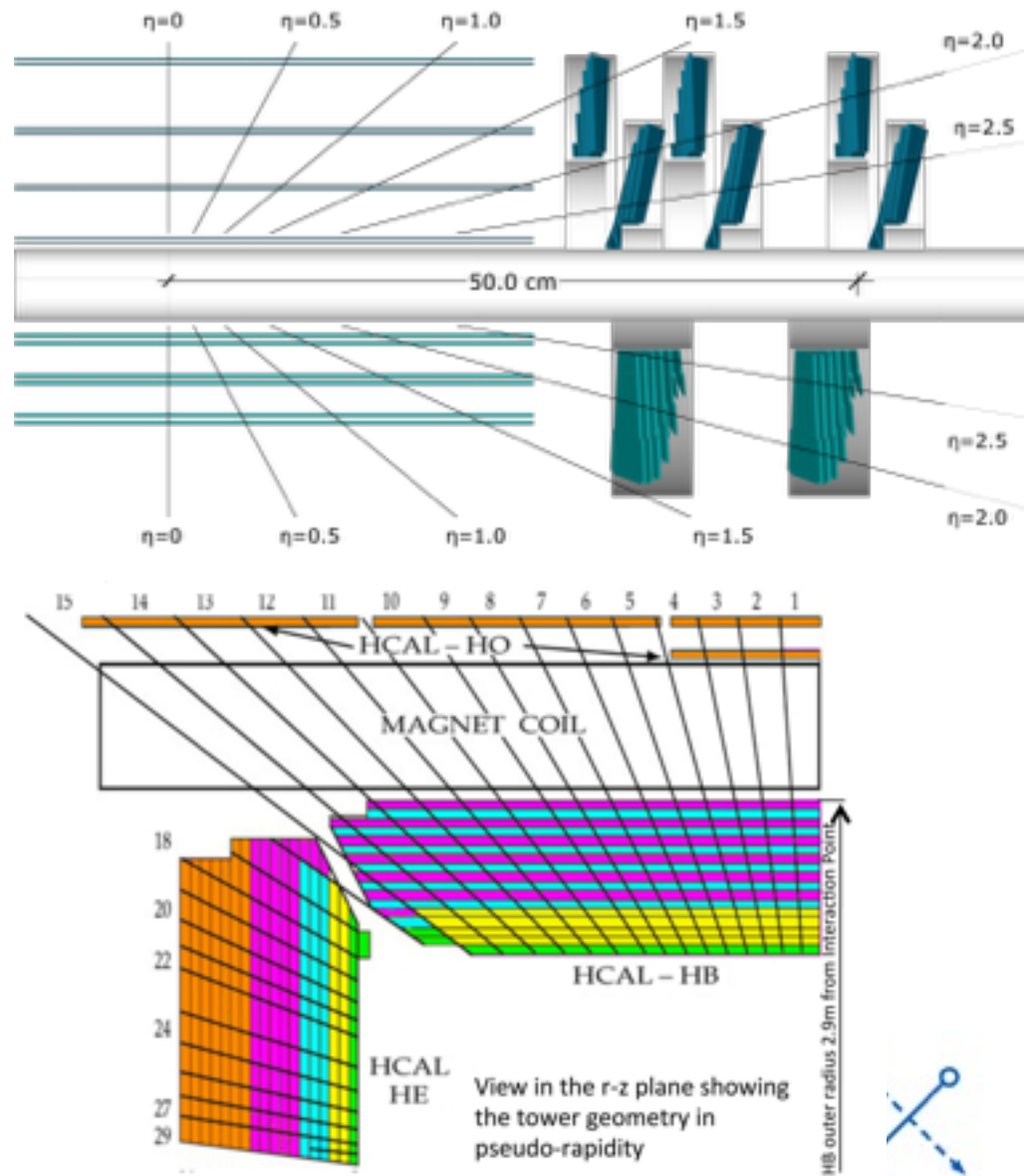
- Cathode strip chambers: electronics upgrade, additional layer
- Drift tubes: electronics upgrade
- Resistive plate chambers: additional layer

## Trigger and DAQ

- New boards (micro-TCA)
- Regional calorimeter triggers
- CSC/RPC/DT track finders for increased mu efficiency
- Upgrade of DAQ electronics

## Luminosity Monitoring

New pixel luminosity telescope  
Replace Beam Scintillator Counters

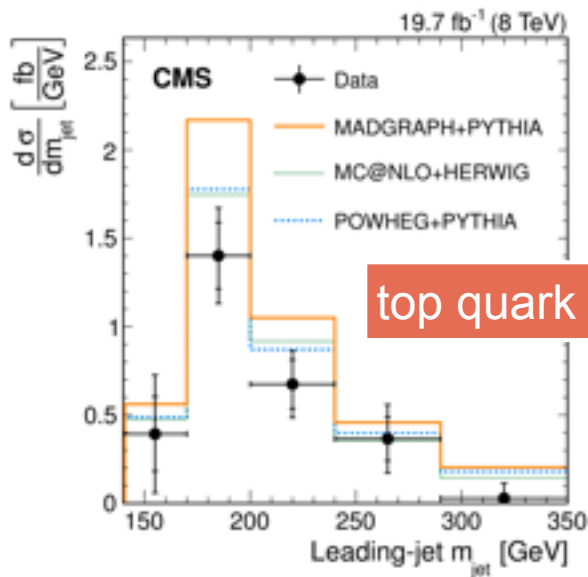
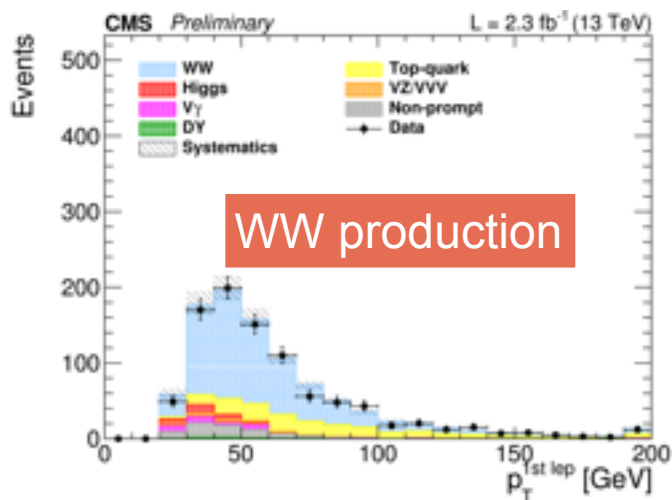
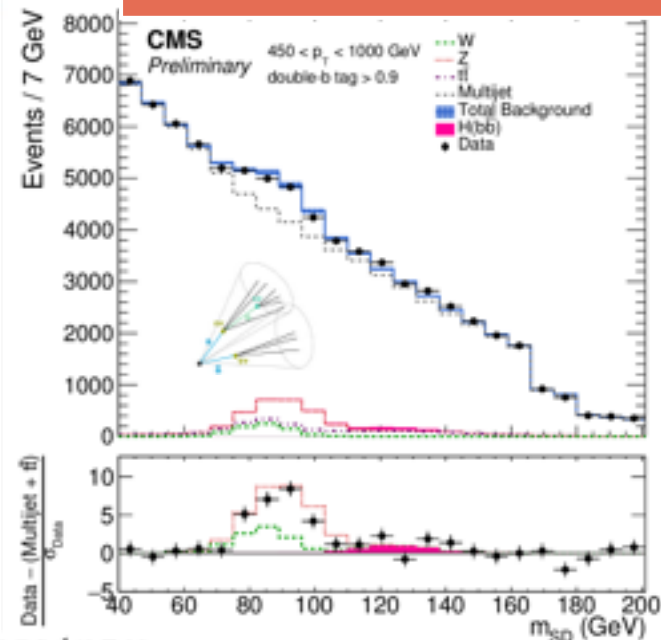




Higgs  
Top quark  
W/Z  
Jets

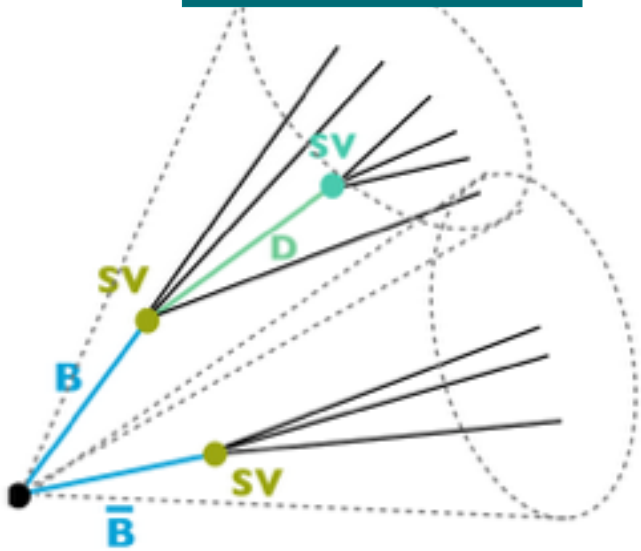
Higher COM energy:  
- Higher cross section  
- Higher energy decay products!  
- Boosted topologies!

First hints of boosted  $H \rightarrow b\bar{b}$

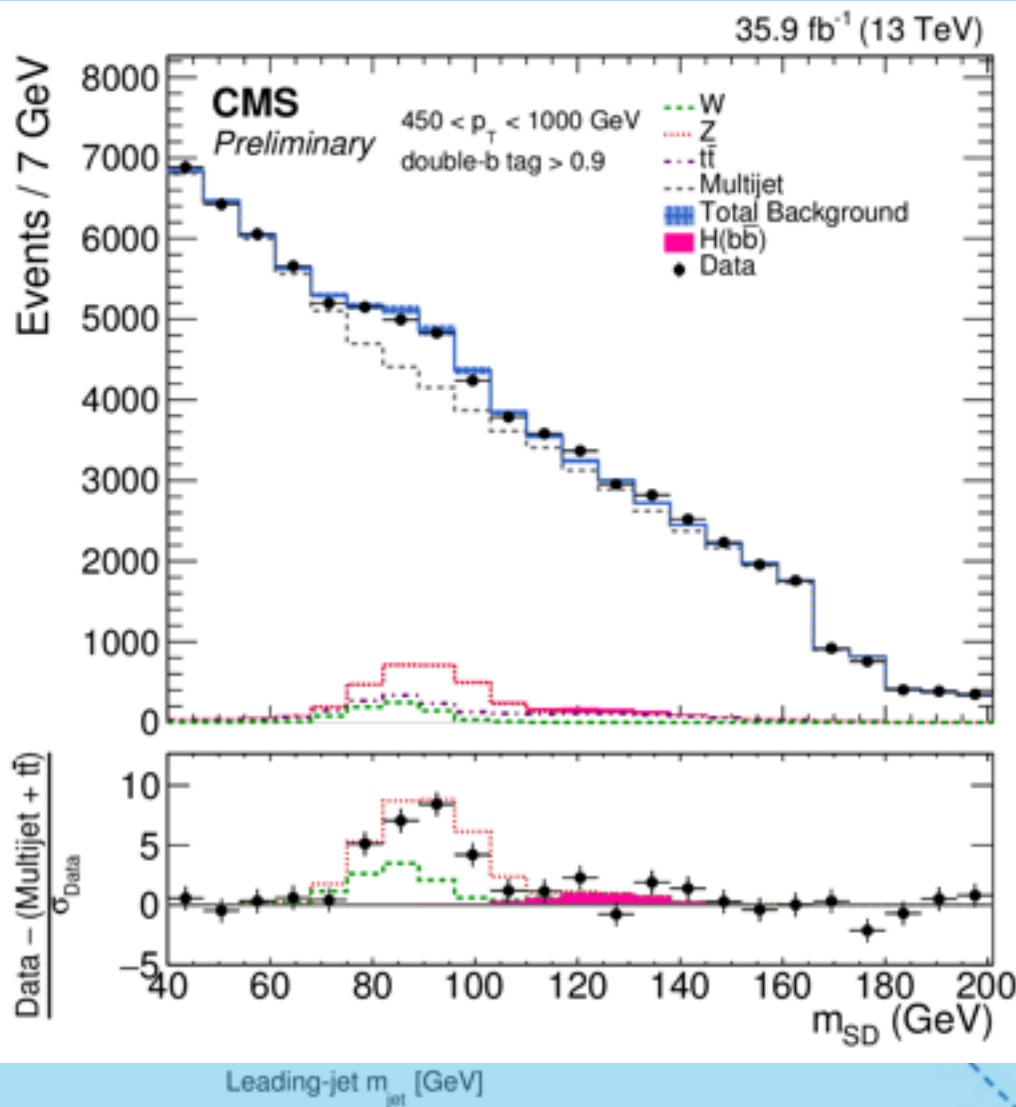
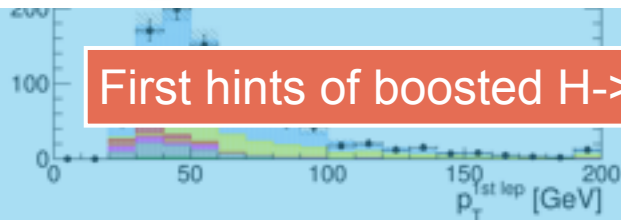


## Higgs

Use massive jets!



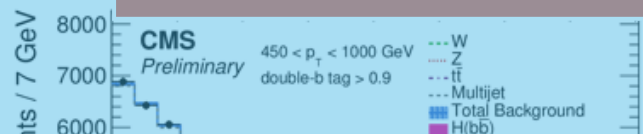
First hints of boosted  $H \rightarrow b\bar{b}$



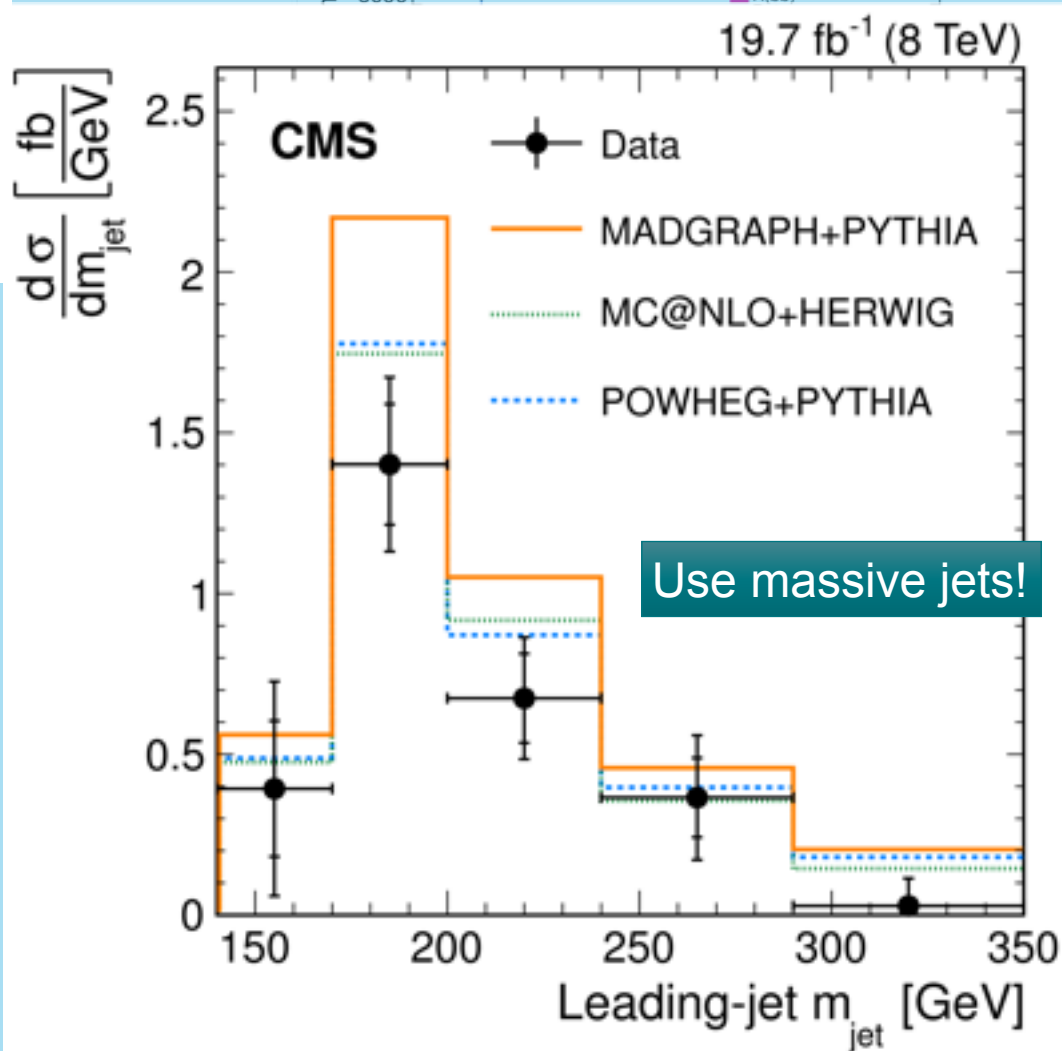
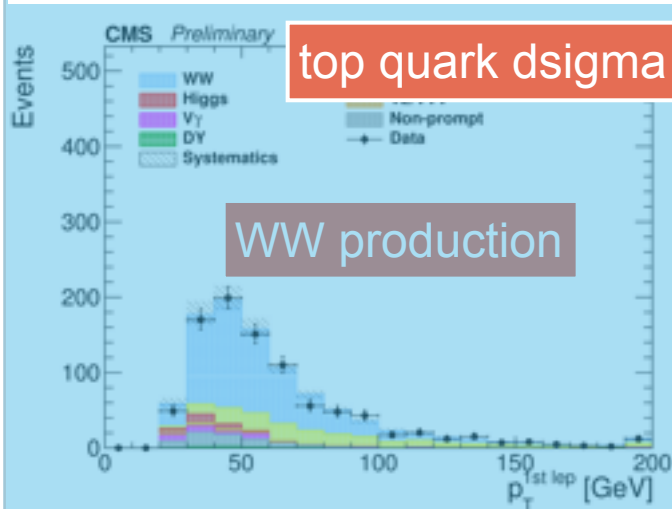
## Reconstruction



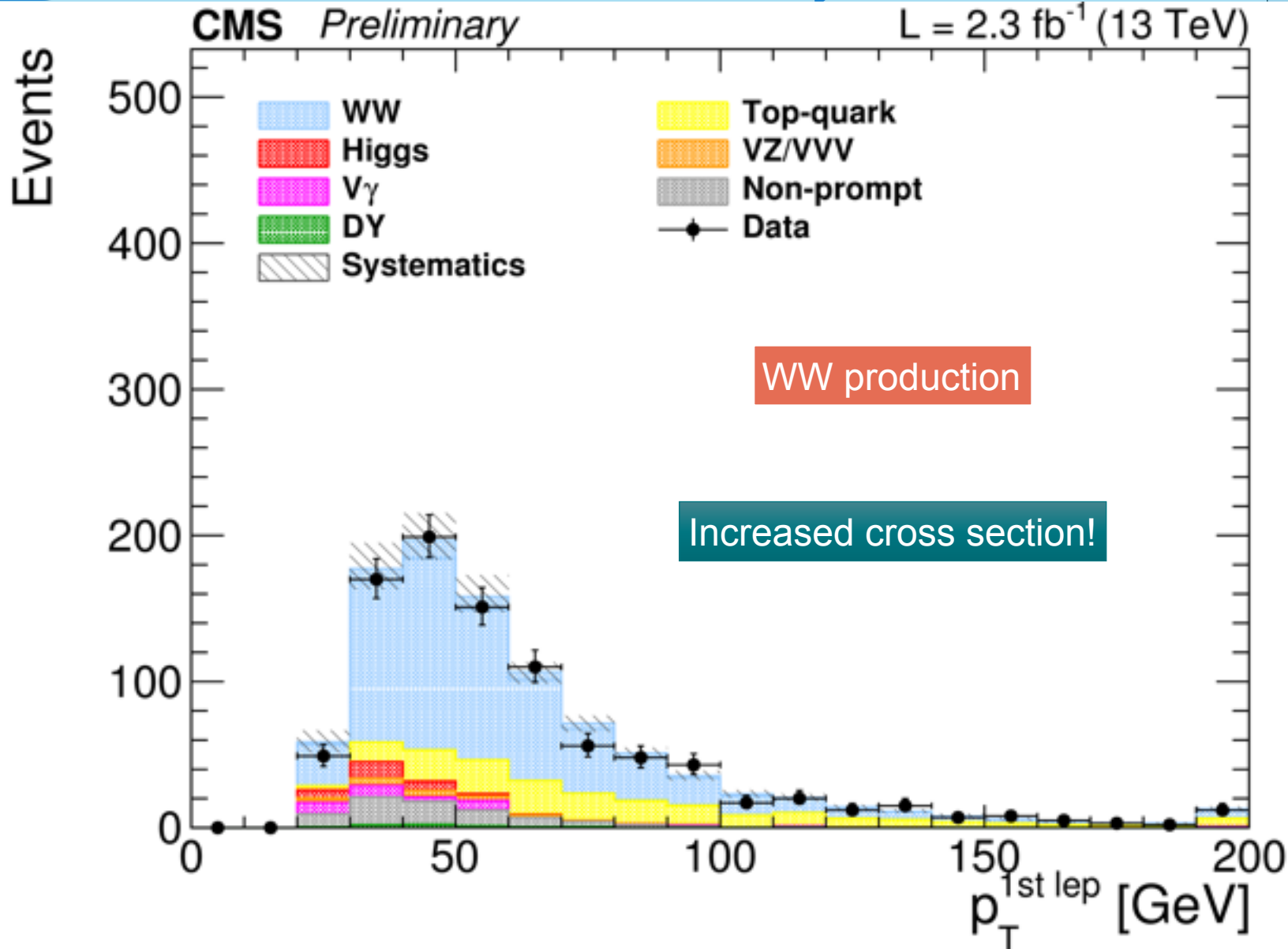
First hints of boosted  $H \rightarrow b\bar{b}$



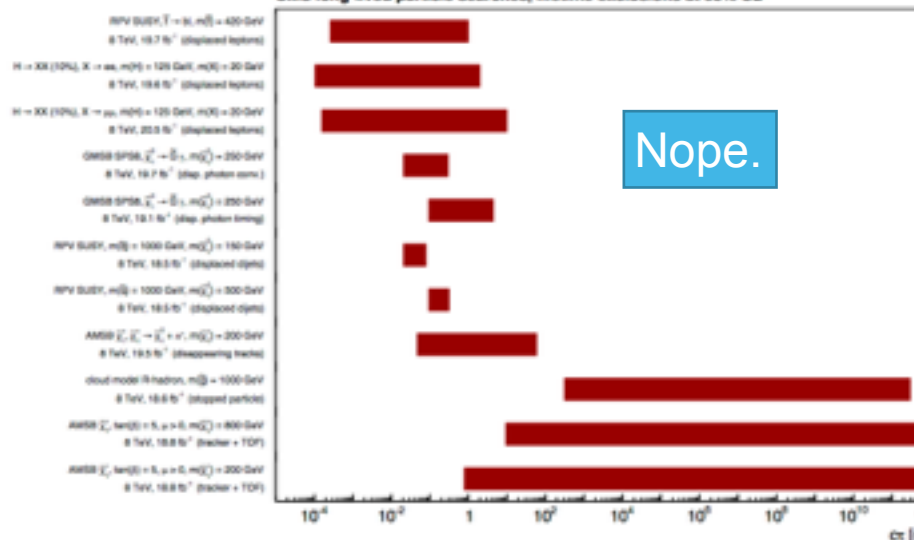
top quark  $d\sigma / d m_{jet}$





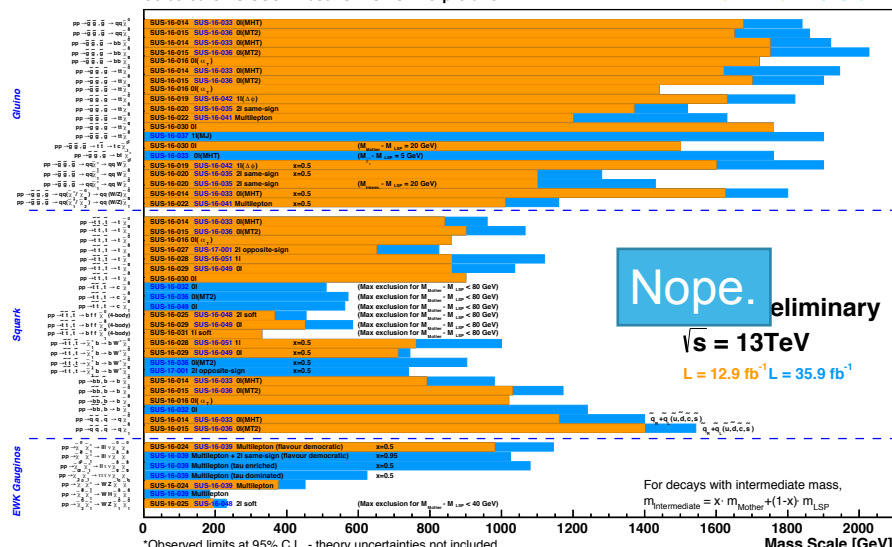


CMS long-lived particle searches, lifetime exclusions at 95% CL

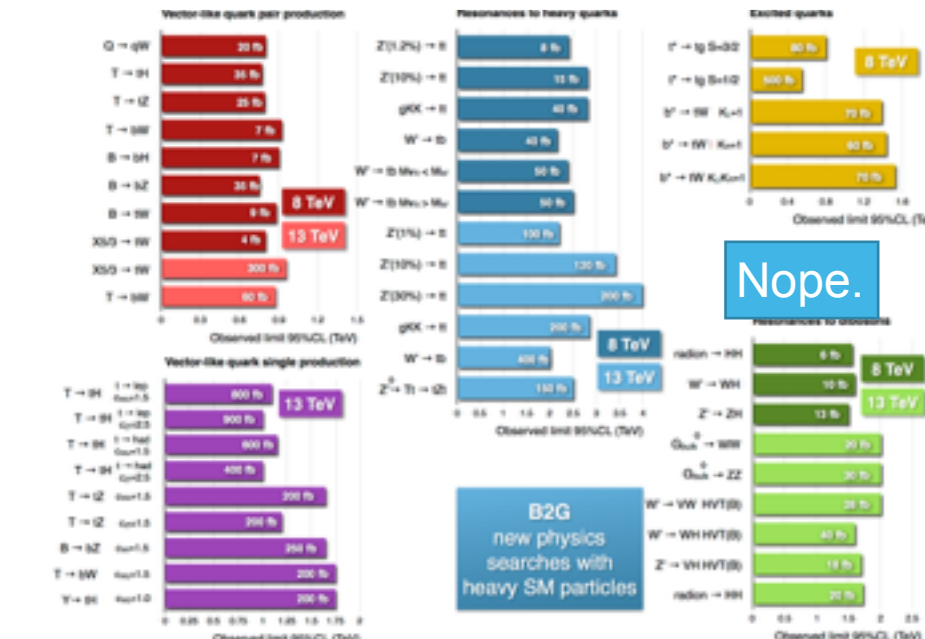


Selected CMS SUSY Results\* - SMS Interpretation

ICHEP '16 - Moriond '17



13 TeV 8 TeV



## What's next?

SUSY: Dead? Hiding? Heavy?

Dark matter: Prospects? Overlap w/DD, ID?

Extra dimensions/strong dynamics: Heavy? Not real?

More Higgses?

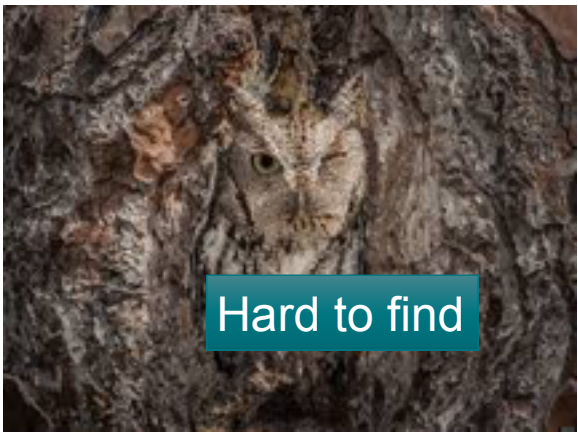
Higgs invisible width?

B physics anomalies?

ttH anomaly?



or



See also Nhan Tran's talk earlier today!



## CMS, LHC, and FNAL

- Why are we still here?

## Past

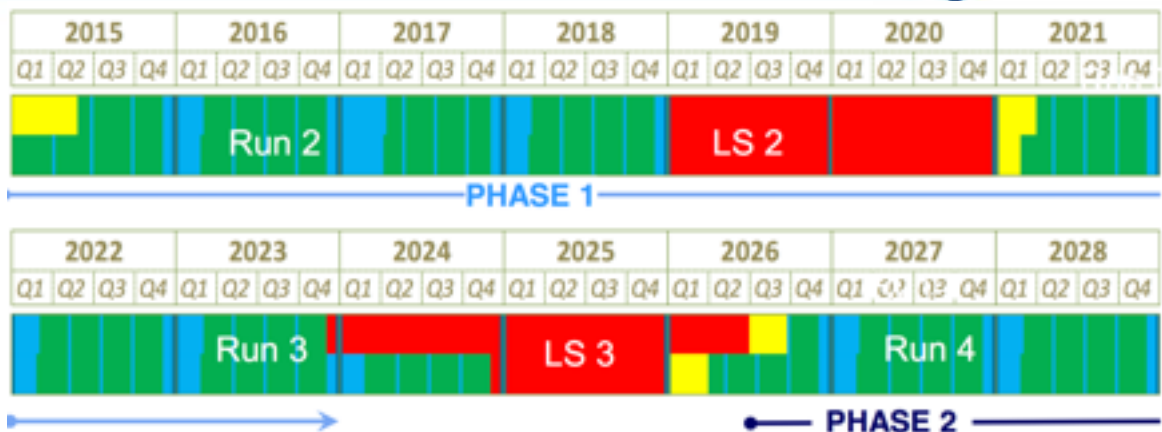
- 2007-2012 (“Run 1”)

## Present

- 2015-2018 (“Run 2”)

## → Future

- >2018 (“Run 3” and High-Lumi LHC)





# The Future: CMS Phase 2 Upgrade



## Tracker

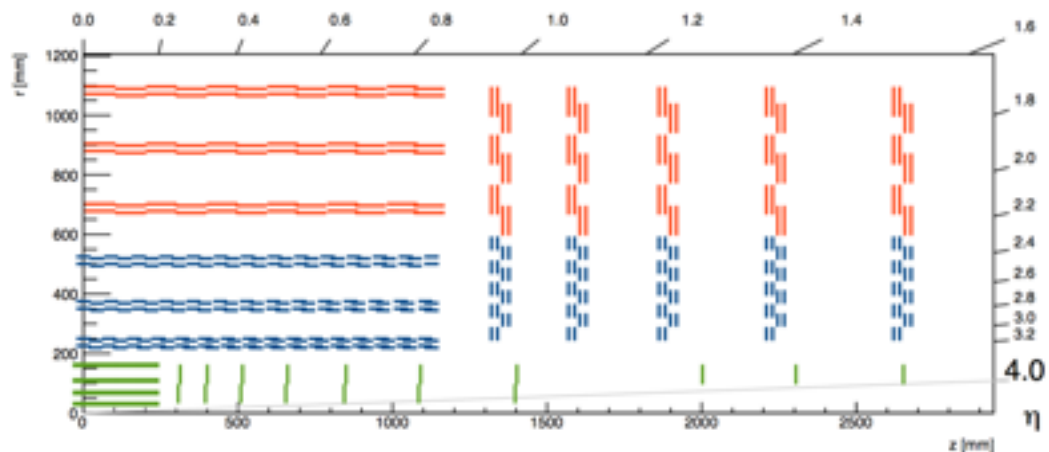
Outer tracker: track stubs at L1, smaller sensors

Inner tracker: extend coverage to  $\eta \sim 4$ , smaller+thinner sensors

## High-Granularity Calorimeter

Copper/tungsten plates w/ Si-based active vol.

“Backing” hadron calorimeter w/ scintillator active vol.



## Muon

Maintain L1 trigger acc for  $\eta$  1.5-2.4:

Add Gas electron multiplier (GEM) chambers, RPCs

Muon extension to  $\eta \sim 3$

## Trigger

Tracking at L1

Higher bandwidth

## Timing Layer

Improves pileup rejection



Also see Petra Merkel's talk this morning!



# The Future: CMS Phase 2 Upgrade



## Higgs:

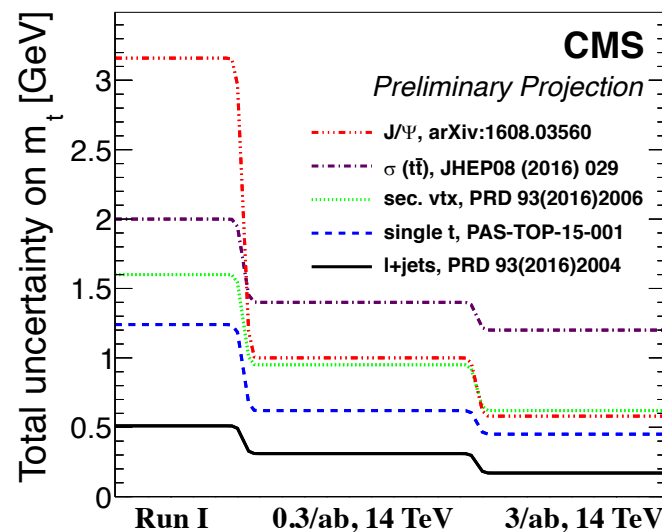
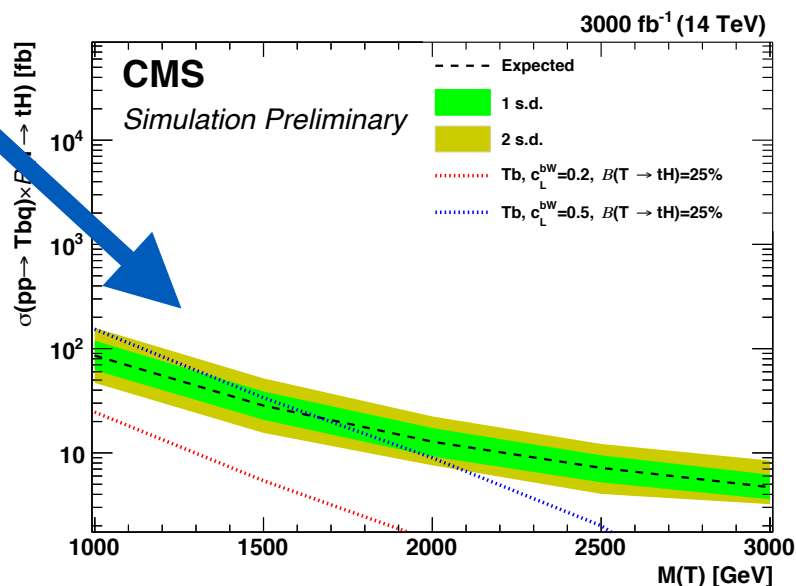
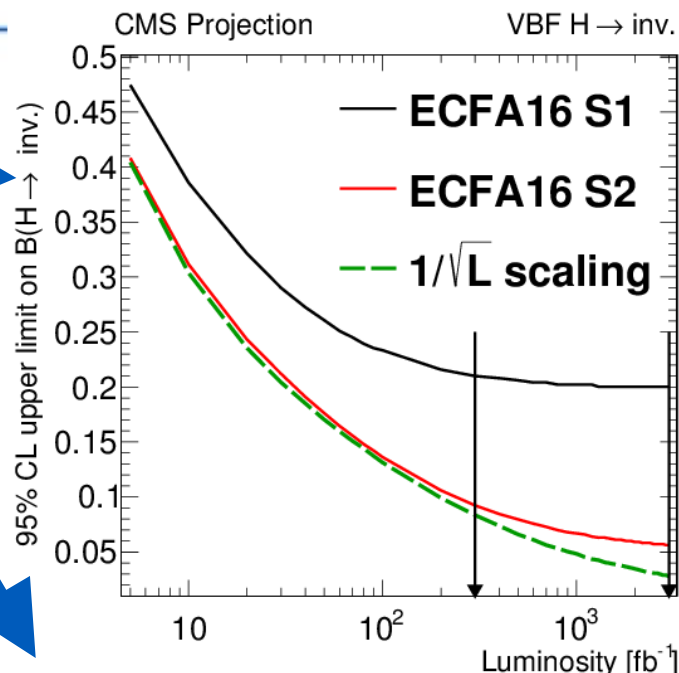
Higgs to invisible  
DM portal  
H mass, cross sections, couplings, etc

## SM :

Top quark mass  
Precision multi-boson production  
measurements

## BSM:

Quark partner masses above natural scale?  
Hidden? Long lived? Very soft? Others?



1985 View of “The Future” (2017):



Styles of 2017

Multiple wristwatches... only tells time!

“Mr. Fusion” cold fusion reactor

Flying car  
(DeLorean)

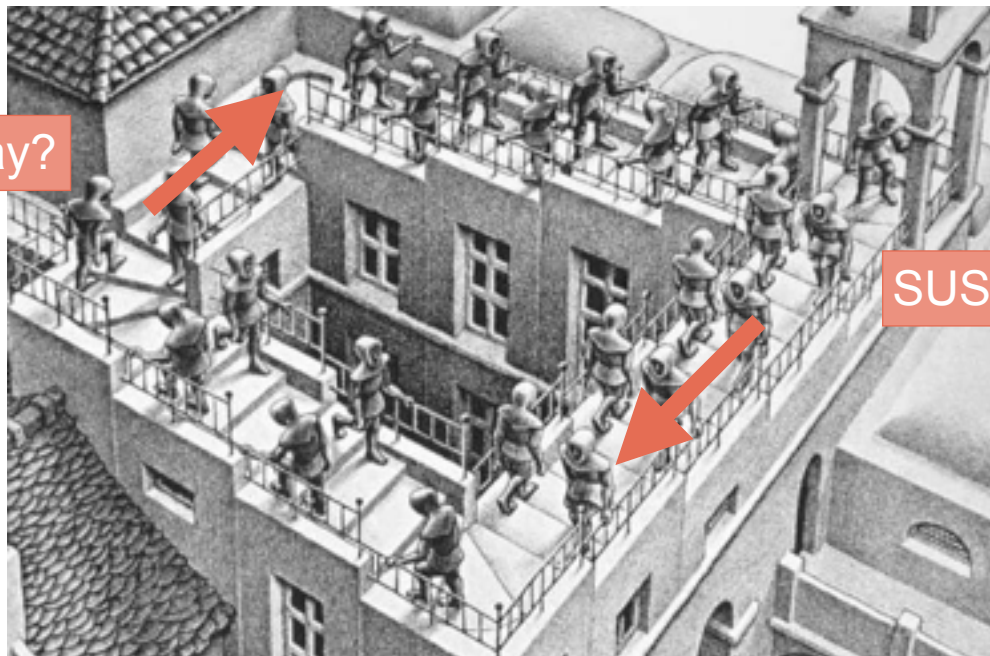




## Next run of LHC:

- Are we still looking for “Mr. Fusion” and flying cars?  
(extrapolation of present ideas of “the future”)
  - Is that what existing BSM models really are?
- Or, are there other aspects we haven’t thought of yet that would show existing models are impossible or implausible?

Light WIMP DM that way?



SUSY this way?



**We all stand on the shoulders of giants.  
Thanks especially to Gino Bolla and  
Simon Kwan, in memoriam, for their  
contributions to the FPIX project here at  
FNAL.**





Parameter	Standard 25 ns	BCMS 25 ns	BCMS 25 ns Pushed	Comments
Energy [TeV]	6.5	6.5	6.5	
$\beta^*$ (1/2/5/8) [m]	0.4 / 10 / 0.4 / 3	0.4 / 10 / 0.4 / 3	0.33/ 10 / 0.33 / 3	Either 40 cm as 2016 or further squeeze to 33cm
Long-range separation [sigma] - assumed emittance	10 sigma - 3.5 um	10 sigma - 2.5 um	10 sigma - 2.5 um	
Half X-angle (1/2/5/8) [ $\mu$ rad]	-185 / 120 / 185 / -150	-155 / 120 / 155 / -150	-170 / 120 / 170 / -150	Went to 140 with lower intensities in 2016
Number of colliding bunches (1/5)	2736	2448	2448	BCMS - 144 bunches/injection from SPS
Bunch population	1.25e11	1.25e11	1.25e11	around 1.3e11 injected for both Standard and BCMS
Emittance into Stable Beams [ $\mu$ m]	3.2	2.3	2.3	Nominal 2.6 for Standard, 1.4 for BCMS at injection
Bunch length [ns] - 4 sigma	1.05	1.05	1.05	As 2016
Peak Luminosity (L0)	1.4e34	1.7e34	1.9e34	
Peak mean pile-up ( <i>inel xsection 80 mb</i> )	37	51	56	Fast decay at start of fill
Average mean pile-up	27	33	36	<b>NB</b> Have to assume average fill length and lumi lifetime. Assume average fill length of 13 hours (June-July 2016 - optimistic)
Average luminosity lifetime (tau)	21 hours	15 hours	14 hours	Approx. - assuming burn only



# We Built FPIX!

The list of US institutions contributed to the FPIX

